A SIMULATION EVALUATION
OF ALTERNATIVE RESPONSES TO TIME-COST VARIANCES
IN STOCHASTIC PROJECT NETWORKS

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Finally, I want to dedicate this work to my lovely wife Marta, who not only typed this work, but, more importantly, showed me the real meaning of the word happiness.

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CHAPTER I

INTRODUCTION

Description of the Problem

In the project planning process, both the Plan itself and the Process by which it is developed are extremely valuable to the project manager in answering many questions of the form: what?, why?, how?, who?, when?, how long?, how much?, and communicating those answers to individuals concerned with the project.

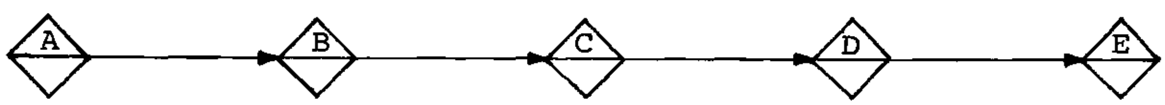
One important element of the project planning process is the time-cost tradeoff problem, the approach that analyzes the opposing effects of certain costs associated with project length (43). Direct costs, such as direct labor, materials and supplies, are related to individual activities. Direct costs tend to increase as the project length is decreased, since providing additional outlays of money in these areas is one way in which the activities can be shortened. Indirect costs generally increase with project length and are not activity specific. Examples of indirect costs include supervision, interest on construction loans and delay penalties. In addition, there is usually a fixed cost associated with undertaking a project. The total cost of the project is the sum of these three costs for the total project length.

When a time-cost tradeoff analysis is performed for a project during the planning stage, a common goal is to develop a plan for performing the project at a project length that minimizes the total project costs.

This thesis concerns itself mainly with project control relative to the time-cost tradeoff solution. The overall objective is to test and compare several methods of correcting deviations from the original minimum cost solution as the project is actually performed.

In order to clarify the problem at hand, an example is presented below in which the whole process of planning and control for a simple project is followed:

Example: Given the following simple network of activities:



Assume all activities have the same quadratic time-cost tradeoff function:

$$DC = C_1 t_e^2 + C_2 t_e + C_3 \qquad t_c \leq t_e \leq t_n \tag{1}$$

where t_c is the crash (i.e., minimum possible) activity duration and t_n is the normal (i.e., minimum direct cost) activity duration. For this particular network, the curve shown in Figure 1-1 is the following time-cost tradeoff function:

$$DC = 15t_e^2 - 240t_e + 1,060 \qquad 2 = t_e = 8 \text{ days} \qquad (2)$$

which is the direct cost curve for each activity in the network. Also assume that the relationship between indirect costs and project length is a linear function:

$$IC = a + b(m)(t_e) \qquad t_c = t_e = t_n \qquad (3)$$

where m is the number of activities. For this example network, the function will be:

$$IC = 100 + 50(5)(t_e) \qquad 2 = t_e = 8 \text{ days} \qquad (4)$$

So the total cost for the whole project would be the function:

$$TC = m(DC) + IC \qquad (5)$$

$$TC = (m(C_1t_e^2 + C_2t_e + C_3)) + (a + b(m)(t_e)) \qquad (6)$$

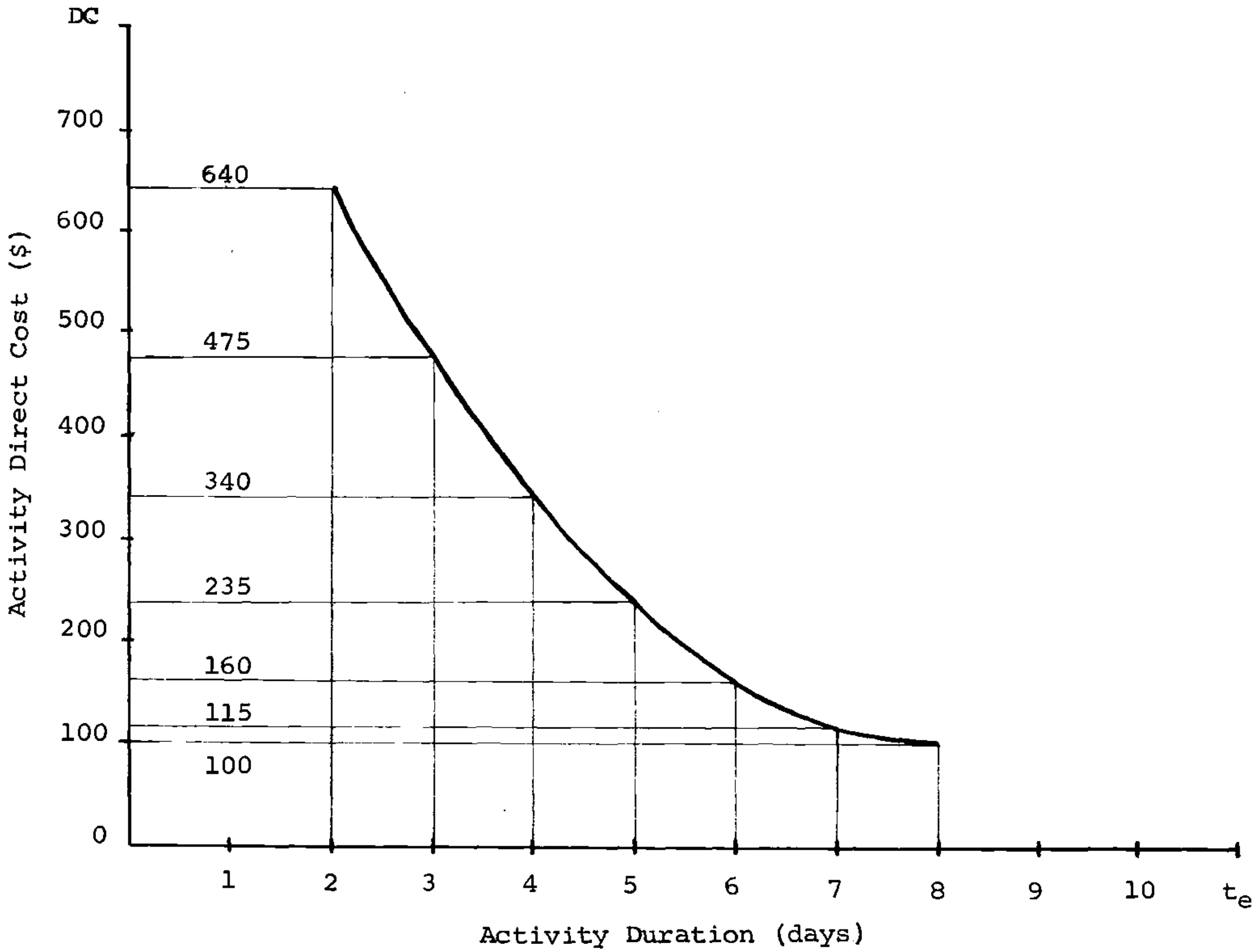


Figure 1-1. Activity Time-Cost Tradeoff Function
$DC = 15\ t_e^2 - 240\ t_e + 1{,}060 \qquad 2 \le t_e \le 8$ days

In order to find the activity duration at which the total project cost is minimized, take the first derivative of total project cost with respect to activity duration, t_e:

$$\frac{d\ TC}{d\ t_e} = 0 = mb + 2mC_1 t_e + mC_2$$

$$t_o = \frac{-(b + C_2)}{2C_1} \qquad t_c = t_o = t_n \tag{7}$$

For this particular network, using the specific direct and indirect cost coefficients, we obtain:

$$t_o = \frac{-(50 + (-240))}{2(15)} = 6.33 \text{ days}$$

Note that 2 = 6.33 = 8 days.

And the minimum total project cost would then be:

$$\begin{aligned} TC &= (5(15t_o^2 - 240t_o + 1{,}060)) + (100 + 50(5)(t_o)) \\ &= (5(15(6.33)^2 - 240(6.33) + 1{,}060)) + (100 + 50(5)(6.33)) \\ &= (5(141.67)) + (1{,}682.50) \\ &= \$\ 2{,}390.83 \end{aligned}$$

Moreover for t_o, the direct cost per activity will be:

$$DC_o = C_1 t_o^{\,2} + C_2 t_o + C_3 \tag{8}$$

For this particular case that becomes:

$$DC_o = 15(6.33)^2 - 240(6.33) + 1{,}060$$

$$DC_o = \$\ 141.67$$

Assuming resources are assigned to each activity to complete it in 6.33 days at a cost of \$ 141.67, the average direct cost per unit of time will be:

$$\overline{DC}_o = DC_o/t_o = \$\ 22.37/\ \text{day} \tag{9}$$

The actual activity duration, however, may deviate from the planned duration. If the <u>actual</u> duration of an activity is t', the <u>actual</u> direct cost will be:

$$DC' = (\overline{DC}_o)(t') = (\$\ 22.37/\text{day})(t'\ \text{days}) \tag{10}$$

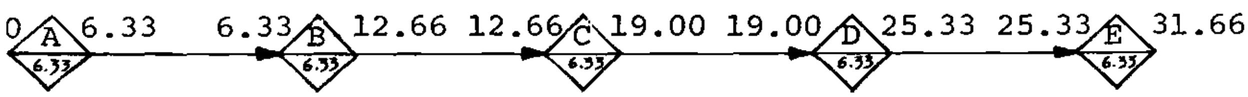
If T' is the <u>actual</u> cumulative project duration, then the <u>actual</u> cumulative project indirect cost will be:

$$IC' = a + b(T') = 100 + 50(T') \tag{11}$$

It should be emphasized at this point that the solutions derived above are valid only for a case such as the one presented in the example, where: the direct costs function is quadratic and it is the same for all the activities; the indirect costs function is linear; and there is only one path of activities in the network.

Assume that a decision is made to try to complete the project in 31.67 days (i.e.: $(m)(t_o) = (5)(6.33 \text{ days})$) so as to perform the project in the minimum total project cost possible of \$ 2,390.83.

At this stage, the planning process is finished, yielding the following project schedule:



With this objective in mind, assume that the project is started, and the project control phase begins. Further assume, for example, that a project update meeting is held after the completion of activity C.

Suppose the durations that the first two activities incurred were 6.33 days each, which agree with the objective set up in the planning stage. However, activity C actually took 7.33 days to be completed, so a delay of 1 day has been incurred.

Altogether then, at the end of day 20 (approximately) when this update meeting is held, the project can be expected to be completed in 32.66 days (i.e., 20 + 2(6.33)), instead of the 31.66 days that were set as the goal.

To calculate the effect of this delay on total costs, the project must be examined on an activity by activity basis, for all activities performed up to this point.

(1) Activities A and B: In the planning phase, the project manager planned a duration of 6.33 days for each of these activities, which implied direct costs of $ 141.67 each. That means that the project manager had assigned to these activities $ 22.37/day in resources for 6.33 days. Since each activity lasted 6.33 days, as planned, they did not have any disruptive effect on the total cost of the project.

(2) Activity C: This activity took 7.33 days to complete, instead of 6.33 days as planned. But the project manager had assigned resources to this activity at a rate of $ 22.37/day. Since the activity took one more day, these direct costs were incurred for one more day. That is $ 22.37/day for 7.33 days, or $ 164.05 rather than $ 141.67.

In order to find the actual total cost at this point, the actual direct costs must be added to the actual indirect project costs. From the information above:

Total project cost incurred after the completion of activity C:

(1) Actual:

Direct costs activ. A = (\$ 22.37/day)(6.33 days)	= \$	141.67 +
Direct costs activ. B = (\$ 22.37/day)(6.33 days)	= \$	141.67
Direct costs activ. C = (\$ 22.37/day)(7.33 days)	= \$	164.05
Indirect project costs for 20 days (approx.)	= \$	1,100.00
Actual Total Project Cost	= \$	1,547.39

(2) Planned:

Direct costs activ. A = (\$ 22.37/day)(6.33 days)	= \$	141.67 +
Direct costs activ. B = (\$ 22.37/day)(6.33 days)	= \$	141.67
Direct costs activ. C = (\$ 22.37/day)(6.33 days)	= \$	141.67
Indirect project costs for 19 days (approx.)	= \$	1,050.00
Expected Total Project Cost	= \$	1,475.01

So, it can be seen that this delay in activity C causes the project to cost: \$ 1,547.39 - \$ 1,475.01 = \$ 72.38 more than planned up to the completion of activity C.

Therefore an obvious question should be asked at this point: how should a project manager react to this situation? Given that (1) a deviation exists between the actual cumulative project duration and the planned cumulative project duration; and (2) a deviation exists between the actual cumulative project cost and the planned cumulative project cost; how should the manager respond to them in order to minimize the total project cost?

The optimum response would involve treating the completed portion of the project as a "sunk cost" and replanning the remainder of the project as if it were a new project. Although the manager cannot alter history, he can attempt to optimize the future. This implies that he should perform an updated time-cost tradeoff analysis for the remaining activities in the project.

For the simple example project presented above, it can be shown that a new time-cost tradeoff analysis will always yield the same optimum solution obtained at the start of the project. This is true because the expression:

$$t_o = \frac{-(b + C_2)}{2C_1}$$

is independent of the number of activities remaining to be performed. In other words, for this simple case the manager should not alter his original plans in response to deviations occurring as a result of the stochastic nature of activity durations. Of course, this "no change" strategy would not typically be the optimum solution to the updated time-cost tradeoff analysis for more complex projects.

Although the performance of updated time-cost tradeoff analyses may be an academically correct element of the project control process, it is not commonly applied or even widely suggested. Most popular texts on project management emphasize methods for documenting the deviations between actual and planned performance. Depending upon the relative importance of the project duration and project cost objectives, the project manager is likely to take corrective action on one of the two deviations without fully understanding the total impact of that action on all dimensions of project performance. For example, if a project is behind schedule, an attempt to speed up could increase direct costs by a greater amount than is justified by the incremental indirect cost associated with the schedule delay. Or if a project is over budget, an attempt to reduce direct costs could delay project completion and thereby increase indirect costs. In any case, corrective actions that do not adequately consider time-cost tradeoffs, including indirect costs, are likely to yield unexpected and suboptimal results.

This study employed stochastic simulation to compare common management responses aimed at correcting time deviations or cost deviations versus an optimum time-cost tradeoff response. Specifically, the following types of responses were compared:

(1) Optimum Time-Cost Tradeoff Response: Treat the remainder of the project as a new time-cost tradeoff problem and determine the new optimum solution for the durations of remaining activities. As explained earlier, the new optimum solution will be the same as the original solution for the simple example problem presented in this section.

(2) Correct Duration Deviation:

a) Fast Response. Attempt to correct the current duration deviation as quickly as possible. Crash the next activity as much as necessary (or down to the minimum duration point) to correct the deviation. In the case of the example problem, since the project is currently one day behind schedule, activity D would be crashed one day, from 6.33 days to correct the deviation.

b) Slow Response. Attempt to correct the current duration deviation at a rate depending on the number of remaining activities in the network. In the example problem, since there are two remaining activities (D and E), the new plan would be to save a half day on each activity. Thus, both activities would be crashed to 5.83 days.

If the project is on or ahead of schedule, no corrective action is taken.

(3) Correct Cost Deviation:

a) Fast Response. Attempt to correct cost deviations as quickly as possible by adjusting direct costs only. Lengthen the next activity as much as necessary (or up to the normal duration point) to lower the direct cost of that activity by the amount of the current cost overrun. For example, this would involve lengthening activity D to try to recover the $ 72.38 additional costs that were incurred because of the delay in activity C. By lengthening activity D from 6.33 days to eight days (the normal time) a total of $ 41.67 can be saved in direct costs. Therefore, activity E must be lengthened also. By lengthening E from 6.33 to 7.145 days $ 30.71 more are saved in direct costs, bringing the total direct cost savings to $ 72.38, which is the amount that had to be recovered. This method does not consider the impact of the corrective action on indirect costs.

b) Slow Response. Attempt to correct the current cost deviation at a rate depending on the number of remaining activities in the network. For example, this would involve adjusting the durations of activities D and E so that \$ 36.19 (= \$ 72.38/2) would be saved on each. This can be accomplished by lengthening each activity from 6.33 to 7.395 days. Again, however, the impact on indirect cost is not considered.

If the project is on or below budget, no corrective action is taken.

Objective

The objective of the study was to compare and evaluate several alternative management responses to time-cost variances in stochastic project networks.

The methodology involved the stochastic simulation of a simple hypothetical project. The decision processes associated with the various management responses were built into the simulation model. The primary criterion for the evaluation of the alternative management responses was the actual _total_ project cost that resulted under each response policy. Other criteria as described in the next section were also applied.

Methodology, Scope and Limitations

The hypothetical network that served as the subject of this study consisted of a simple, one-path network, with 10 activities. Each activity had the same duration distribution, which was a Beta distribution. Each activity had the same time-cost tradeoff function, which was quadratic. The use of a single-path network is not as severe a limitation as it may initially appear to be, since most projects in the real world tend to have a single critical path that dominates all other paths. Thus, controlling a single-path network is much the same as controlling a project with a dominant critical path from the time-cost tradeoff point of view.

One of the five management response modes described earlier was selected at the start of each run. Each model run began by performing a time-cost tradeoff analysis, to develop an initial optimum solution. Then, the model simulated the project. It stepped through the activities, performing each activity stochastically in terms of activity durations. The model calculated actual costs based on the stochastically generated activity durations in conjuction with the planned cost per day (which was a measure of resource loading). After each activity, the model compared the expected cumulative project duration and cost (from the initial optimum solution) with the actual cumulative project duration and cost up to that point.

If a negative time or cost deviation was found (depending on the response mode selected), the model attempted to correct the deviation encountered, utilizing the response mode previously assigned. After these calculations were performed, the model moved on to the next activity and repeated the process until all activities were simulated and project was finished. Thirty project replications were performed for each mode. The results were averaged for each mode and the means were the basis of comparison.

After all five response methods had been simulated, the set of base runs was complete. Then, the results were tested for their sensitivity to:

(1) The variances of the activity duration distributions.

(2) The slope of the activity duration-direct cost tradeoff relationships.

(3) The slope of the project duration-indirect cost relationship.

(4) The number of activities in the network.

In each of the above cases the variable in question was replaced and the model was replicated 30 times with each response mode as before. The new set of runs was compared with the set of base runs and the sensitivity of the results to each variable was evaluated.

It is important to note here that the four sensitivity tests were run separately and independently of one another.

The GASP IV computer language was selected for use due mainly to it's efficiency and ease of application to this problem. The model is fully documented in Chapter III.

The five methods tested here could be compared in a number of ways. The primary criterion for the evaluation of the alternative management responses was: the average actual total project cost. The objective here was to keep it as close as possible to the minimum total project cost possible for the given network conditions, (i.e., the initial optimum solution).

Some other detailed criteria of interest were:

(1) The average actual direct project costs.

(2) The average actual project duration.

(3) The variation in results from run to run. This is the sensitivity of each method to the stochastic nature of the simulation, measured as the variance in total project costs (or durations) recorded for each method in the 30 simulation iterations performed for each model.

(4) The sensitivity to:

a) Changes in variance of activity duration distributions.

b) Changes in the steepness of activity time-cost tradeoff functions.

c) Changes in the steepness of the project duration-indirect cost function.

CHAPTER II

LITERATURE SURVEY

Introduction

A vast amount of literature exists on the subject of network based project management. In this survey the purpose is to review representative literature in this area, followed by a more detailed discussion of the literature that relates specifically to the time-cost tradeoff problem.

Thus, the literature survey is divided into three sections as follows:

Project Management

Time-Cost Tradeoff Analysis

Project Control

Project Management

At the turn of the century, Henry L.Gantt, a disciple of Frederick W.Taylor, made many contributions to Scientific Management. He was the inventor of the Gantt Chart, a technique that permits the display of data required for scheduling purposes in manufacturing operations.

The Gantt or Bar Chart was one of the first formal scheduling models used by management. It was a powerful tool for planning and controlling industrial operations. The Gantt Chart was most successfully applied to production operations of a highly repetitive nature.

Primarily, the Bar Chart was designed to control the time element of a program. There were other approaches which evolved from it, such as the Line-of-Balance and the Milestone Methods (43, p.17 and 24). Neither the Gantt Chart nor these other methods were highly successful on non-repetitive projects, especially those that had a high engineering content. The main problem is that these methods do not show precedence relationships or dependencies among activities.

Due to these deficiencies, the network concept became necessary. The huge size of many present-day programs (containing thousands of significant activities, possibly taking place in widely separated locations) no longer permits the treatment of interdependencies implicitly. This holds true also for relatively small projects subjected to very detailed planning.

The network approach to project management can be attributed to two separate projects - one undertaken by the U.S. Government, the other by industry. Both groups advocated the use of a network depicting clearly the relationship among various activities. PERT (Program Evaluation and Review Technique) (38) and CPM (Critical Path Method) (27,28,29) were both developed during 1957-58, but completely independently of each other. PERT was originally designed for the Navy's Polaris Research and Development Program, whereas CPM was designed for a construction project at Du Pont.

CPM (Critical Path Method)

This procedure was jointly developed in 1957 by the Du Pont company and Remington Rand Univac. It was initiated by Kelly and Walker (27,28,29) and later extended by Levy, Thompson and Wiest (35). The objective of the CPM research team was to determine the best way to reduce the time required to perform routine plant overhaul, maintenance, and construction work. Basically they were interested in determining the optimum tradeoff of time (project duration) and total project cost. This amounts to determining the duration of a project which minimizes the total project cost (composed of the sum of the direct and indirect costs). For example, direct costs include labor and materials, while indirect costs include the usual overhead, as well as the cost of production time lost due to plant downtime.

In CPM activity durations are considered to be deterministic for a certain level of resource utilization. By varying the amount of resources allocated for direct cost items, the duration and the direct cost of the activity could be changed. Kelly and Walker (27) introduced the functional relationship between project cost and time by defining, for each activity, limits for time and cost called "normal" and "crash". Kelly (29) further developed this to a parametric linear programming formulation to obtain the project cost curve. Fulkerson (16) developed a similar analysis. Both Kelly and Fulkerson assumed that a project's time-cost tradeoff is a continuous, convex function which can be represented accurately by a piece-wise linear approximation.

Roper (54) simplified and modified Fulkerson's algorithm. Roper's algorithm not only produces the project cost curve, but it also produces sub-project cost curves.

Meyer and Shaffer (42) used integer linear programming to study project cost functions. However, with algorithms existing at the time of their study, they state that projects of 50 or more activities can not be handled.

Some extentions of CPM include the work of Gessford (17), who concluded that "medium and large construction firms may find it economically and administratively advantageous to add cost constraints to their existing CPM/Time Systems",and an article by Kleinschmidt, Moore and Tamashanas (33), who introduced cash flow into CPM and applied it to make or buy decisions.

PERT (Program Evaluation and Review Technique)

Admiral W.F. Raborn recognized the need for a better integrated planning and control system for the Polaris Weapons System Program. To face this challenge, a research team was assembled consisting of representatives of Lockhead Aircraft Corporation (prime contractor for Polaris), the Navy Special Projects Office, and the consulting firm of Booz, Allen, and Hamilton. The technique resulting from this research project was designated as PERT.

PERT was formally defined by Malcolm, Roseboom, Clark and Fazar (38). It was originally designed to be time-oriented; that is, it did not give much consideration to factors of cost and availability of resources. The main difference between PERT and CPM is that in CPM activity durations are deterministic, whereas in PERT activity durations are subject to a probability distribution. The definition of this probability distribution is based on the system of three time estimates-normal, optimistic and pessimistic. The authors assumed a Beta distribution for activity durations. They suggested that the probability of completing a project by a certain date can be computed by invoking the central limit theorem. Assuming that the distributions of activity durations along the critical path are independent, the distribution of project durations will be approximately normal. The mean of the project duration distribution will be equal to the sum of the means for the activity distributions along the critical path and the variance will be equal to the sum of the critical activity variances.

PERT assumptions were discussed by Murray (47) and by MacCrimmon and Ryavec (36, 37). They performed rigorous analyses of the PERT assumptions, and developed some suggestions that may lead to more accurate time estimates and probability statements. Clark (5) used different assumptions than the original PERT assumptions, the main difference being his assumption that the activities in the network are normal random variables. By approximating the Beta distributed variables with normally distributed variables, Clark developed an iterative procedure to obtain the expected value and variances of a network with reasonable accuracy. Moder and Phillips (44, p.229-239) provide an illustrative application of this procedure.

In a different article, Clark (6) makes an attempt to validate the probability statements of PERT. Grubbs (19) has pointed out the subjective nature of the PERT estimation problem and the restrictions on the Beta distribution. But McBride and McClelland (41) argue that the Beta distributions associated with PERT are not necessarily as restricted, and the differences between the PERT values of expected time and standard deviation and the exact values for the associated Beta distribution are not as great, as has previously been indicated in the literature.

While MacCrimmon and Ryavec were working on a comprehensive analysis of PERT assumptions, Van Slike (60, 61) was exploring the use of Monte Carlo methods to yield solutions to the PERT problem. He showed that the Monte Carlo estimate of the mean project length is unbiased. Another outcome of his research is the "criticality index" for each activity, which is the probability that the activity will be on the critical path.

The PERT procedure always leads to an optimistically biased estimate of the earliest (expected) occurrence time for the network events. This is the merge event bias; it arises because all subcritical paths are ignored in making the forward pass computations. This bias is insignificant if the longest path leading to a merge event is much longer than the second longest path, and/or the variance of the activities on the longest path is small. Hartley and Wortham (21) made an attempt to remove the biases in PERT assumptions. They attempted to synthesize various contributions in this area and developed a statistical theory for the derivation of an unbiased distribution of the project completion times.

A different direction was taken by Wilson (30) and by

King, Vittebrongel and Hezel (31), they looked into the behavioral aspect of time estimating. Their papers fulfilled the long-felt need to research the estimating behavior of individuals in relation to PERT assumptions. The conclusion of these two papers is that there is no significant change in the accuracy of estimating the remaining portion of an activity as the portion of activity remaining becomes smaller.

Some extensions of PERT include PERT Cost (12) and PERT Reliability (39). PERT Cost adds the considerations of costs to the schedule produced by PERT; however, it does not provide probability information relative to cost. There is no attempt to use cost data to optimize total project costs. PERT Reliability is an extension of PERT into Reliability Management.

The above distinctions between CPM and PERT are primarily of historical interest. During the past few years a merging of these two techniques has taken place, and the result is, in most cases, referred to as a PERT-type system. In the remainder of this thesis, such network based planning systems will be referred to simply as project networks or PERT networks.

Simulation

Van Slyke's (60,61) application of digital simulation to project management was mentioned above in connection with PERT assumptions. Other references of interest in this area are cited here.

Trilling (58) describes a job shop simulation of orders that involve activity networks. In this paper, a coding procedure is described based on binary numbers and the networks represented are defined by the routings of shop orders. Several decision rules are tested.

Hicks and Jain (24) reported the application of GPSS to project management. They considered a number of examples of complex precedence relationships employing a GPSS/360 program. They conclude that GPSS/360 can be employed to develop project management information not easily attainable employing standard project management techniques.

An interesting application of Monte Carlo simulation to investment risk analysis is reported in the work of Hess and Quigley (23). They worked out an example in which the distribution of a certain profitability criterion was obtained where analytical techniques had failed because of complexity. Clark (7) made a similar analysis for the case of two investments, in which the cash flows follow a probability distribution. Using Monte Carlo simulation, he obtained the probability distribution of the rate of return for each investment.

Burt and Garman (3) examined methods for solving the stochastic PERT problem. These methods have usually followed one of three basic approaches: analytic, approximation, or Monte Carlo methods. All are intended to avoid a difficult multivariate integration, which is the most general solution technique. In cases when analytic methods are unsuitable and the uncertainties of approximation can not be tolerated, there is no choice but to turn to numerical integration to solve the PERT problem. Due to the multivariate nature of the integrals, their difficult regions of integration, and limitations on computing resources, simulation is normally employed in their evaluation.

Ringer (53) showed that the integration could be expressed in a simpler form by conditioning on particular activity times. This concept was also developed independently by Burt and Garman (3), and they describe and evaluate a technique for performing this multiple integration. The concept of conditioned random variables has been used extensively in the theory of probability and statistics. Its application to simulation was first suggested by Troter and Tukey (59). Burt and Garman here illustrated the method for stochastic networks.

The usefulness of conditional Monte Carlo depends upon the number of "unique activities" in a given network. A unique activity is one which lies only on a single path. In their algorithm Burt and Garman set the non-unique activities (in a network of activities with stochastic durations) to constant durations by sampling them and fixing the random variables at mean values. So the completion time of the network is then said to be "conditioned" on the fact that those non-unique activities have taken on these sample mean values. Hence a new conditional Monte Carlo estimate of the network completion time is formed. When using this estimate, only the samples of the unique activities are needed per realization; that is, less than those required for the straightforward simulation estimate, which requires samples of all activities.

From the application of their algorithm, Burt and Garman conclude that the conditional Monte Carlo procedure reduces the amount of sampling necessary to obtain given levels of accuracy in the estimation of critical path time cumulative distribution functions via simulation, as compared to the straightforward simulation (also called crude Monte Carlo simulation).

Kiviat and Pritsker (32) introduced GASP II which is a Fortran based simulation language. This language was later expanded by Pritsker (51) into GASP IV. Whereas the GASP II language included only discrete event simulation, the GASP IV language includes both continuous and discrete capabilities. This thesis utilizes the discrete capability of the GASP IV language to simulate the project network under study.

GERT (Graphical Evaluation and Review Technique) is an important example of technological spin-off from space science research. GERT is a combination of network theory, probability theory, and simulation to yield a readily applicable modern management tool for systems analysis. GERT was initially developed by Pritsker for a study of the terminal countdown of an Apollo space system (14,50). It has become apparent that many of the features provided by GERT can be incorporated into industrial systems analysis. The GERT technique includes the modeling of systems in network form and analysis through simulation. Since its introduction, GERT has been revised and considerably extended. It's most recent general version is GERTS IIIZ (50), which is a totally self-contained computer program requiring only input data describing the system being studied. Thus, GERT has the distinct advantage that model manipulation and analysis is easily accomplished.

In GERT nodes are considered to have an input and an output side, each characterized by certain logical relationships with respect to connecting jobs. Two types of output sides are used, which determine the type of branching that occurs from the node. Deterministic branching is used when all activities emanating from a node will be undertaken. Probabilistic branching is used when only one of the several emanating activities is to be performed.

Specialized versions of GERT include Q-GERT, for analyzing queueing and logistics problem, and P-GERT, for project planning using precedence networks.

Time-Cost Tradeoff Analysis

A somewhat more detailed discussion is presented here and in the next section, since those areas are more directly relevant to the present study.

Davis (10) performed a literature survey of the various solutions that have been proposed for each of the three cases of the resource allocation problem. these three cases are:

(1) Time-cost tradeoff analysis (unconstrained resources),

(2) Resource leveling subject to constraints on project duration,

(3) Minimization of project duration subject to stated resource constraints.

In this survey Davis attempts an assesment of progress to date as well as pointing out potential future courses of development. The review is aimed more at a presentation of the basic concept and approach involved in each technique than a detailed examination of the computational steps involved.

Davis concludes that: " 1. A wide variety of analytical solutions are available for the time-cost tradeoff problem.

2. An equally wide variety of heuristic solutions exist for the constrained resource allocation problems."

The nature of the time-cost relationships was described by Lamberson and Hocking (34). The authors are concerned with a common problem encountered in project scheduling, as follows:

> From the initial estimates for activity times, the total project duration can be determined. If this duration is too long due for contractual or technological reasons, the project must be compressed in some optimal manner. The problem reduces to one of buying time along the critical paths at minimum cost. (34, p.597)

Lamberson and Hocking recognized that the time-cost relationships are non-linear and are usually convex to the origin. Based on this fact the authors developed an algorithm to perform a time-cost tradeoff analysis for any project duration where the tradeoff functions are not necessarily linear. The algorithm presented by the authors is an application of an algorithm developed by Hartley and Hocking (20) for solving convex programming problems. Lamberson and Hocking conclude that their algorithm is computationally advantageous over other methods to solve the time compression problem, such as the separable programming algorithms, (for example see (26)). This makes the algorithm amenable to time compression in large project networks.

There are many papers in the literature in which the author modifies slightly a time-cost tradeoff algorithm developed elsewhere, improving the solution to the problem or changing certain assumptions of the model. For instance, Goyal (18) modifies an algorithm described by Siemen (55) for shortening the duration of a project when the expected duration of the project exceeds a predetermined limit. The objective in both cases is to minimize the total cost of expediting activities in order to complete the project in the desired time. Goyal suggests an alternative technique to Siemen's algorithm, which allows for "de-shortening" a previously shortened activity. By employing the procedure described in Goyal's article there is apparently less path over-shortening than with Siemen's approach.

At times, the existence of time-cost tradeoffs, has been treated with considerable skepticism in the literature. But many authors have demonstrated the existence of a negatively sloped function for the time-cost tradeoff of most, if not all, projects in the real world.

Teece (57) wrote a paper on this subject in which reasons are presented for the existence of a time-cost tradeoff during the design, construction, and start-up of a manufacturing plant abroad. Some of the reasons advanced are as follows:

(1) When uncertainty precludes immediate identification of the best design, it may be desirable to "hedge" by supporting several different designs. By incurring higher project costs, hedging can reduce the project time relative to a procedure

which explores different designs sequentially.

(2) Besides "hedging" activities there are a number of other procedures which can be used to reduce project time, but they can all be expected to increase project costs. For example, as additional engineers are brought onto the project to speed up the design, diminishing returns can generally be expected. Also attempts to reduce project time by speeding equipment procurement can also be expected to increase costs.

All of these reasons provide the foundation for postulating a time-cost tradeoff that within some range has a negative slope and is convex to the origin. Teece introduced a model to estimate this tradeoff for the establishment of a manufacturing plant abroad. Using data from a sample of twenty such projects the parameters of the tradeoff function were estimated.

Furthermore, Teece demonstrated that the elasticity of this tradeoff can be explained by reference to characteristics of the technology being transferred and to characteristics of the participating firms. The elasticity estimates were generally greater than one, indicating that time shaving would involve rather high incremental costs. It was also observed that the elasticity estimates were highest for projects where the technology had not been previously commercialized, for projects that were large, and for projects carried out by larger firms.

Project Control

Along with the earliest CPM and PERT systems, came the development of such technically complex areas as: time-cost tradeoff and statistical schedule predictions. But it took more time for the relatively simpler and generally more applicable area of project cost control to gain significant attention.

The initial major push to arouse interest in network cost control was provided by some U.S. Government agencies. The Department of Defense and the National Aeronautics and Space Administration jointly issued a manual (12) which emphasized the cost control aspects of "PERT-type systems". The result of this major initiative was the prompt generalization of the use of PERT Cost procedures, which soon became a requirement in certain military research and development projects, with several new computer programs being written.

Industry however took a bit longer to become interested in the cost control potential of project networks. A little impetus in this direction was provided by the U.S. Army Corps of Engineers (49) by formalizing its interest in "Network Analysis Systems" for schedule and cost control. Eventually, PERT Cost procedures became more generalized in industry and other areas.

As cost-control systems became more generalized, several inadequacies were found in many of the systems being used. Davis (11) outlined some of those problems explaining their causes and how a proper project cost control system should be carried out. Davis advocates the use of Trend Analysis as the crucial tool to controlling project costs:

> It tends to remove the bias of tight or loose schedules,low or high cost estimates, and good or bad performance. The typical result of trend analysis is to get management disturbed much earlier than it otherwise would be. This early warning prompts management to invoke control measures while a great number of options are open. (11, p.129)

Furthermore, Davis explains the importance of three other aspects of cost control systems, as follows:

(1) Identifying total costs. Looking at the case of engineering cost overruns, the author shows how it's effect upon total cost is often underestimated because "the ripple effects are underestimated". In other words, a change in a preliminary engineering design feature may cause huge additional costs in materials, equipment, production and alterations to the system; but these costs are not considered as part of the engineering costs. To eliminate this problem, Davis suggests the use of "work breakdown packages". These are packages which can be utilized from the proposal stage through the completion of the project to give a uniform basis for providing the current estimate. Within each package, an engineering task is required to quantify

all design decisions in terms of the cost determinations which result. The engineer can release a work package only after summarizing the total cost change which has resulted from his work on that package.

(2) Short range scheduling. Once good standards have been established, engineering cost control should focus on obtaining a performance that meets or betters these standards. To accomplish this Davis suggests the short range scheduling of engineering work in intervals of as little as one-half hour. Using such a breakdown, it would be easier for the engineer to track his own progress toward the completion goal. Consideration should be given for the time that the engineer will require in other activities (aside from the project work load), when scheduling the engineer's time.

(3) Assign a project manager. The project manager should be assigned during the proposal stage. He must be supported by an accurate and advanced estimating system. He must also have the support of top management; that is, he must have authority.

An interesting paper was written by Burt (4) in which a model is developed which involves three aspects of project management:

1. Uncertainty: the time required to complete an activity is seldom known in advance with certainty. This is particu-

larly the case for typically non-repetitive "once-in-a-lifetime" projects.

2. Resources: the time required to complete most activities is seldom independent of the resources allocated to them. The allocation of limited resources amongst "competing" activities is a primary function of the project manager.

3. Decision making is not a static concept: over the duration of a project, the project manager sequentially reallocates (constrained) resources in light of new information on the status of the project. Resource allocation in projects is seldom executed in the immutable manner of a "budgeting" process. (4, p.249)

For Burt, the random variable of interest is T, the time to complete the entire project. The primary objective considered in his paper is the minimization of the expected project completion time, E(T). For a given network, the efficacy of various allocation rules are measured in terms of the resulting E(T).

Four resource allocation decision rules were tested via simulation. He defined them as follows:

1. STATIC. This first allocation rule did not involve sequential decisions and, as such, it served as a base against which Burt judged the efficacy of the dynamic rules, which follow.

2. DYNAMIC. This rule made resource allocations to the first activity on each path by the same method as STATIC. However, resources were sequentially allocated to subsequent activities by examining information on the realized times for activities already completed.

3. LAGFIRST. The third allocation rule was a modification of DYNAMIC whereby the first activity on each path received only a fraction (50 percent) of the resources which would be allocated to it under the DYNAMIC or STATIC procedure.

LAGFIRST then made sequential allocation decisions in an identical manner to DYNAMIC.

4. SEQLAG. The final decision rule tested, was an extension of LAGFIRST. As with LAGFIRST, the first activities were allocated only 50 percent of the amounts that were allocated under STATIC or DYNAMIC. Under SEQLAG, subsequent activities were then given increasing fractions of the allocations that were made under DYNAMIC. (4, p. 253-254)

The last three allocation rules involved sequential allocations of resources to subsequent activities.

Each of the four allocation rules was used in the processing of several projects whose networks consisted of pairs of parallel paths. The number of activities on each of the parallel paths ranged from two to six. In each situation, 1,000 realizations of the project's completion time were obtained via simulation.

From the simulation results, Burt obtained the following conclusions:

1. Sequential rules can reduce expected project completion time and such rules can lead to substantial reductions in the variance of project completion time.

2. Limiting resource allocations made early in a project can also lead to reductions in project completion time, somewhat at the expense of increased variance.

3. Projects which contain relatively large numbers of activities on various paths are most amenable to control by sequential resource allocations.

4. Likewise, sequential allocation rules will be relatively most effective for projects which contain activities whose processing times are highly variable. (4, p.257)

Using simulation, Burt has demonstrated that sequential decision rules may be used for resource allocation and that they can reduce expected project completion time as well as the variance of a project completion time. This thesis involves a similar approach, but the primary criterion for the evaluation of alternative control policies was the total project cost rather than project duration. The thesis explicitly recognizes that, because of the tradeoff between direct and indirect costs, the minimum project duration does not generally produce the minimum project cost.

CHAPTER III

METHODOLOGY

The GASP IV computer language was selected for use in the simulation model. The author assumes in this thesis that the reader is familiar with this language. For a complete description of the GASP IV language, see Pritsker (51).

This thesis utilizes the discrete event simulation capability of the GASP IV language to simulate the project network under study. There are several reasons for the selection of GASP IV for this study, such as:

(1) GASP IV provides functional capabilities for: event control, information storage and retrieval, system state initialization, statistical computations and report generation, random deviate generation; as well as some other functional capabilities which will not be used in this particular study.

(2) GASP IV is FORTRAN based and is easy to learn, understand, program, analyze and revise.

(3) GASP IV's simulation power permits great computational speed, and facilitates run replications.

Model Formulation

The model is composed of the main program and the various subroutines. These subroutines are either GASP IV subprograms: GASP, DATIN, CLEAR, FILEM, COLCT; or user-written subroutines: INTLC, EVNTS.

In this chapter the main program and the two user-written subroutines will be presented in detail, emphasizing how they interact with the functions and subroutines provided by GASP IV.

It is important to point out that the model has only one event which is the completion of an activity. Therefore the EVNTS subroutine is used as the event subroutine, rather than using it to decode the event type as is normally done in GASP IV.

The user-written portion of the model is shown in Appendix A along with a complete alphabetical list of terms and definitions.

Main Program

The main program initializes those non-GASP variables that remain constant for all projects in each simulation run. The planning phase of the project is represented as a series of calculations to determine the optimum total project duration and cost.

It should be noted that the project network under study, has several characteristics that are similar to the network presented in the example of Chapter I of this thesis (p.2). More specifically, the network in the model also has the following characteristics:

(1) All the activities have the same quadratic time-cost tradeoff function.

(2) The relationship between indirect costs and project length is a linear function.

(3) The project network consists of only one path of activities with Beta distributed durations.

Due to these similarities, several of the equations introduced for the example in Chapter I, also apply to the planning phase of the network under study. In the main program, the first computation determines the optimum activity duration, using equation (7) of Chapter I.

```
TOPT = -(B + C2)/(2.0*C1)
```

TOPT - The optimum activity duration (days).
B - The slope of the indirect cost function ($/day).*
C1,C2,C3 - Coefficients of the quadratic activity duration-direct cost tradeoff function ($/day^2, $/day, $).*

* Model inputs.

The activity durations in the model are Beta distributed random deviates. For each simulation run, the optimum mean of the activity duration distribution (TOPT) is computed. The range of the Beta distribution is determined by factors that specify the minimum and maximum values as fractions of the mean. The difference between the maximum and minimum factors is multiplied by the optimum mean (TOPT). The range is then divided by six to estimate the standard deviation of the Beta distribution. By squaring this standard deviation the variance of the distribution is determined.

```
VAR = (((BMXFAC - BMNFAC)*TOPT)/6.0)**2.0
```

VAR - Variance of the Beta distribution of activity durations (days^2).
BMXFAC - The maximum value of the Beta distribution of activity durations expressed as a multiple of the mean of that distribution (dimensionless).*
BMNFAC - The minimum value of the Beta distribution of activity durations expressed as a fraction of the mean of that distribution (dimensionless).*

* Model inputs.

The direct costs associated with the optimum, normal and crash activity durations respectively, are computed using the quadratic activity duration-direct cost function (Equation (1) of Chapter I) for each case.

```
COPT = C1*(TOPT**2.)+ C2*TOPT + C3
CNORM = C1*(TNORM**2.)+ C2*TNORM + C3
CCRSH = C1*(TCRSH**2.)+ C2*TCRSH + C3
```

COPT - Direct cost associated with the optimum activity duration ($).
CNORM - Direct cost associated with the activity

normal (i.e., minimum direct cost) point ($).

TNORM - The normal (i.e., minimum direct cost) activity duration (days).*

CCRSH - Direct cost associated with the activity crash (i.e., minimum duration) point ($).

TCRSH - The crash (i.e., minimum possible) activity duration (days).*

* Model inputs.

The expected total project duration is determined by multiplying TOPT by the number of activities in the network.

EPD = 10.0*TOPT

EPD - Expected total project duration assuming optimum activity durations (days).

The expected total project cost at completion is computed by:

(1) Multiplying COPT by the number of activities in the network to obtain the expected direct cost at completion, and

(2) Adding the indirect cost at completion, which is calculated by plugging EPD into equation (4) of Chapter I.

EPC = (10.0*COPT)+(A + B*EPD)

EPC - Expected total project cost at completion, assuming optimum activity durations ($).

A - The fixed component of the indirect cost function ($).*

* Model input.

At the end of the project planning stage, the main program calls upon subroutine GASP.

```
NRN = O
CALL GASP
```

NRN - Number of the current run (project) replication (dimensionless).

Subroutine GASP is the executive routine of GASP IV. It calls subroutine DATIN which initializes all GASP IV variables for the simulation run. (See printout of information read by DATIN in appendix A). Subroutine DATIN calls the user-written subroutine INTLC.

Subroutine INTLC

Subroutine INTLC is used to initialize non-GASP variables at the start of each project replication. First it determines whether the project replication corresponds to the start of a new management response mode. If so, the mode switch is incremented. Then subroutine CLEAR is called to clear the statistical storage arrays. The random number generator is reinitialized, so that the same sequence of random numbers is generated for all response modes.

```
IF(NRN.GT.O) GO TO 200
MODE = MODE + 1
CALL CLEAR
X = DRAND(-1)
```

```
MODE          - Switch for determining manage-
                ment response mode, where:
                MODE = 1  indicates optimum mode.
                MODE = 2  indicates fast duration
                          correction.
                MODE = 3  indicates slow duration
                          correction.
                MODE = 4  indicates fast cost cor-
                          rection.
                MODE = 5  indicates slow cost cor-
                          rection (dimensionless).
X             - Dummy variable used only in resetting
                the random number generator (dimension-
                less).
DRAND(ISTRM)  - GASP IV function that generates pseu-
                dorandom numbers on the interval (0,1)
                from stream ISTRM. A call to DRAND
                with a negative argument causes the
                generator to be reinitialized.
```

The simulation clock, the actual direct cost accumulator, and the activity counter are set to zero at the beginning of a new project replication.

```
200 TNOW = 0.
    CNOW = 0.
    NACT = 0
    NRN = NRN + 1
```

```
TNOW - Current time (days).**
CNOW - Cumulative actual direct costs ($).
NACT - Number of the activity just completed
       (dimensionless).
```

** A GASP IV variable.

Then subroutine INTLC computes the parameters to schedule the completion of the first activity in the new project replication. TOPT is set as the mean of the Beta distribution of activity durations from which the next activity duration will be generated. The minimum and maximum values of activity durations are then determined by applying the BMXFAC and BMNFAC fractions to the mean of the distribution. The differences between these maximum, mean and minimum values are calculated to facilitate computations required later in the model. The variance is then computed for this Beta distribution, using the procedure explained above in the MAIN program.

```
BMU = TOPT
BMN = BMNFAC*BMU
BMX = BMXFAC*BMU
DBA = BMX - BMN
DBM = BMX - BMU
DMA = BMU - BMN
VAR = (DBA/6.0)**2.0
```

BMU - The mean of the Beta distribution of activity durations from which the next activity duration will be generated (days).

BMN - The minimum value of the Beta distribution of activity durations (days).

BMX - The maximum value of the Beta distribution of activity durations (days).

DBA - Difference between the maximum and minimum values of the Beta distribution of activity durations (days).

DBM - Difference between the maximum and mean values of the Beta distribution of activity durations (days).

DMA - Difference between the mean and minimum values of the Beta distribution of activity durations (days).

An array of parameters is then defined, as required by GASP IV (51, p.55) for the Beta distribution from which a random deviate is desired. The parameters are referred to as a parameter set. The first argument of the array designates the parameter set. The second argument designates the specific argument within the set, as required by GASP IV.

```
PPARM(1,1) = (DMA/DBA)*((DMA*DBM/VAR)- 1.0)
PPARM(1,2) = BMN
PPARM(1,3) = BMX
PPARM(1,4) = PPARM(1,1)*DBA/DMA
```

PPARM(1,I) - Parameters required by function Beta to generate stochastic activity durations from the appropriate Beta distribution.**

** GASP IV variable.

An event is then created with two attributes. The first attribute is the scheduled event time (i.e., the time of completion of the first activity). For this first attribute, a Beta deviate is generated using parameter set number 1 and random number stream number 1. The second attribute of the event, is the actual direct cost of the activity. The direct cost is computed as the actual duration of the activity multiplied by the planned direct cost per day. Then GASP IV subroutine FILEM is called to place the attribute vector into file 1. This file is used by subroutine GASP to move the project to the next event.

```
ATRIB(1) = BETA(1,1)
ATRIB(2) = ATRIB(1)*(COPT/TOPT)
CALL FILEM(1)

RETURN
END
```

ATRIB(I) - The attributes of the next simulation event, specifically the completion of the next activity, where:
ATRIB(1) = scheduled time of completion (days).
ATRIB(2) = actual direct cost of the activity ($).**

BETA(1,1) - GASP function which generates a Beta deviate using parameter set 1 and random number stream 1 (days).

** GASP IV variable.

Subroutine INTLC returns control to subroutine DATIN, which returns control to subroutine GASP. At this point GASP first determines whether it is time to stop the simulation and print the results. If not, subroutine GASP removes the next event from file 1 and places its attributes into the ATRIB(I) vector. GASP then advances the clock (TNOW) to the scheduled event time contained in ATRIB(1) and calls subroutine EVNTS.

Subroutine EVNTS

This is the most complex subroutine in the model. This subroutine is normally used to decipher an event code and call the appropriate event subroutine. As mentioned earlier, however, there is only one type of event in this particular model. Therefore, EVNTS is used as the event subroutine itself.

Subroutine EVNTS simulates the performance of each activity in the project. As the model steps through each activity, the number of activities remaining to be processed in the project is computed. Then the expected time at which the current state of completion should have been reached is determined. The deviation between the expected and simulated actual time at which the current state of completion was reached is calculated and expressed as a percentage of the expected time.

```
50 NACT = NACT + 1
   REMACT = 10 - NACT
   ETIME = NACT*TOPT
   TDEV = ETIME - TNOW
   PTDEV = 100.0*(TDEV/ETIME)
```

REMACT - Number of activities remaining to be processed in the project (dimensionless).
ETIME - Expected time at which the current state of completion should have been reached, assuming optimum activity durations (i.e., originally scheduled completion time for the activity just completed) (days).
TDEV - The deviation between the scheduled and actual time at which the current state of completion was reached (days), where:
$TDEV > 0$ indicates ahead of schedule.
$TDEV < 0$ indicates behind schedule.
PTDEV - TDEV as a percentage of ETIME (%).

Then the simulated actual cumulative direct cost for the project is updated by adding the direct cost associated with the activity being processed, which was earlier stored in

ATRIB(2). The cumulative simulated actual total cost is computed by adding to the previous value the actual indirect costs associated with the current duration. The expected total project cost at the current state of completion is determined and the deviation between actual and budgeted cumulative total project cost is determined and expressed as a percentage of the expected total project cost for the current state of completion.

```
CNOW = CNOW + ATRIB(2)
CCNOW = CNOW +(A + B*TNOW)
ECOST = (NACT*COPT)+(A + B*ETIME)
CDEV = ECOST - CCNOW
PCDEV = 100.0*(CDEV/ECOST)
```

CCNOW - Cumulative actual total cost (\$).
ECOST - Expected total project cost at the current state of completion assuming optimum activity durations (\$).
CDEV - The deviation between actual and budgeted cumulative total project cost at the current state of completion (\$) where:
CDEV $\geq$ 0 indicates budget $\geq$ actual.
CDEV $<$ 0 indicates budget $<$ actual.
PCDEV - CDEV as a percentage of ECOST (%).

Subroutine EVNTS then determines whether all activities have been performed for the project. If the project is not finished, the subroutine identifies the sequence of operations that should be employed for the particular response mode assigned.

```
   IF(10 - NACT) 700,700,10
10 GO TO(100,200,300,400,500), MODE
```

Management response mode 1 is the optimum response mode. the optimum time-cost tradeoff response is to treat the remainder of the project as a new time-cost tradeoff problem and determine the new optimum solution for the durations of remaining activities. For the simple project network under study, however, it was shown in Chapter I that a new time-cost tradeoff analysis will always yield the same optimum solution obtained at the start of the project. Therefore, the model simply reassigns TOPT as the mean of the Beta distribution of activity durations from which the next activity duration will be generated, and proceeds to the next activity.

```
100 BMU = TOPT
    GO TO 600
```

Mode 2 is the fast response to correct duration deviations. Here the model attempts to correct the current duration deviation as quickly as possible. First it determines whether the project is ahead or behind schedule at the current state of completion. If the project is on or ahead of schedule, the model does not attempt to correct the duration deviation. TOPT is reassigned as the mean of the Beta distribution of activity durations from which the next activity duration will be generated, and the next activity is processed. If the project is behind schedule, (TDEV is a negative value), the model crashes the next activity as much as necessary (TOPT + TDEV) to correct the duration deviation or down to the minimum activity duration (TCRSH). The larger of these two values is then assigned as the new mean of the Beta distribution from which the next activity duration will be generated.

```
200 IF(TDEV) 201,100,100
201 BMU = AMAX1(TOPT + TDEV,TCRSH)
    GO TO 600
```

AMAX1 - Fortran library function that identifies the larger of several values and assigns it to the respective variable.

Response mode 3 is the slow response to correct duration deviations. The model attempts to correct the duration deviations at a rate depending on the number of remaining activities in the network. If the project is on or ahead of schedule, the model again does not attempt to correct the duration deviation. TOPT is reassigned as the mean of the Beta distribution, and the next activity is processed. If the project is behind schedule, the model subtracts the current time (TNOW) from the expected total project duration assuming optimum activity durations (EPD). This remaining time is then divided by the number of activities remaining to be processed in the project (REMACT). Once this value is determined the model compares it to the minimum activity duration (TCRSH). The larger of these two values is selected as the new mean of the Beta distribution of activity durations from which the next activity duration will be generated.

```
300 IF(TDEV) 301,100,100
301 BMU = AMAX1((EPD - TNOW)/REMACT, TCRSH)
    GO TO 600
```

Model 4 is the fast response to correct cost deviations. Here the model attempts to correct the current cost deviation as quickly as possible by adjusting direct costs only. If the project is on or below the budgeted costs, the model does not attempt to correct the cost deviation. TOPT is reassigned as the mean of the Beta distribution and the next activity is processed. However, if the project is above the budgeted amount for the current state of project completion (CDEV is a negative value), the model reduces the amount of resources available for the next activity's direct costs as much as necessary (COPT + CDEV) to correct the cost deviation, or down to the minimum direct cost point (CNORM). Control is then transferred to statement number 550, which is shown following the explanation of response mode 5. The new target for activity direct cost (CNEXT) is plugged into the quadratic activity duration-direct cost function, and the quadratic formula is used to solve for the activity duration that will yield the desired cost. (The lower of the two roots of the quadratic equation is used, since we are dealing with the negatively sloped portion of the quadratic curve.) This activity duration is then assigned as the mean of the Beta distribution from which the next activity duration will be generated.

```
400 IF(CDEV) 401,100,100
401 CNEXT = AMAX1(COPT + CDEV, CNORM)
    GO TO 550
```

CNEXT - Target direct cost for the next activity ($).

Management response mode 5 is the slow response to correct cost deviations. The model attempts to correct the current cost deviation at a rate depending on the number of remaining activities in the network, by adjusting direct costs only. Again if the project is on or below the budgeted costs, the model simply reassigns TOPT as the mean of the Beta distribution. But if the project is above the budgeted amount for the current state of completion of the project (CDEV is a negative value), the cost deviation is divided by the number of remaining activities to determine the amount by which the direct cost of each remaining activity must be reduced. The model reduces the direct cost of the next activity by this amount (COPT +(CDEV/REMACT)) or down to the minimum direct cost level (CNORM).

This new direct cost target (CNEXT) is plugged into the trade-off function (as was explained for mode 4 above), and the root of the quadratic function is assigned as the mean of the Beta distribution from which the next activity duration will be generated.

```
500 IF(CDEV) 501,100,100
501 CNEXT = AMAX1(COPT + (CDEV/REMACT), CNORM)

550 BMU = (- C2 - SQRT(C2**2.0 - 4.0*C1*(C3 - CNEXT)))/
         /(2.0*C1)
```

SQRT - Fortran library function that computes the square root of its argument.

Once the mean of the Beta distribution for the duration of the next activity has been determined (regardless of the response mode used), subroutine EVNTS recomputes the parameters required by function BETA. This involves the same computations as those used previously in subroutine INTLC for the first activity in the project. Note that the range of the distribution varies in proportion to the mean.

```
600 BMN = BMNFAC*BMU
    BMX = BMXFAC*BMU
    DBA = BMX - BMN
    DBM = BMX - BMU
    DMA = BMU - BMN
    VAR = (DBA/6.0)**2.0
    PPARM(1,1) = (DMA/DBA)*((DMA*DBM/VAR)- 1.0)
    PPARM(1,2) = BMN
    PPARM(1,3) = BMX
    PPARM(1,4) = PPARM(1,1)*DBM/DMA
```

The model determines the expected direct cost for the next activity based upon the mean of the Beta distribution of activity durations. Then a Beta deviate is generated to be assigned as the simulated actual duration of the next activity.

```
EXPCST = C1*(BMU**2.0)+ C2*BMU + C3
ADUR = BETA(1,1)
```

EXPCST - Expected direct cost for the next activity based upon the mean of the Beta distribution of activity durations ($).

ADUR - The actual duration of the next activity (days).

The two attributes of the next event are now created. The first attribute is the time at which the event (completion of the next activity) will occur (TNOW + ADUR). The second attribute is the actual direct cost of the activity which is the actual duration of the activity (ADUR) multiplied by the planned direct cost per day (EXPCST/BMU). Then GASP IV subroutine FILEM is called to place the attribute vector into file 1.

```
ATRIB(1) = TNOW + ADUR
ATRIB(2) = ADUR*(EXPCST/BMU)
CALL FILEM(1)
RETURN
```

The computations shown above in subroutine EVNTS are repeated sequentially for each of the activities in the project network.

After each activity, the model prints the absolute and percentage deviations in current duration and cost (TDEV, PTDEV, CDEV, and PCDEV). The statements which produce this output are not shown here.

After the last activity has been processed for a given project, the model prints the total project duration and total project cost for that project. Then GASP IV statistical subroutine COLCT is called to record the actual project duration and total cost. This subroutine is utilized later to obtain statistics summarizing the 30 replications of the project under each response mode.

```
CALL COLCT(TNOW,1)
CALL COLCT(CCNOW,2)
```

Then the model determines how many replications of the project have been performed under the current response mode. If the number of replications is less than 30, subroutine EVNTS calls subroutine INTLC, and a new project is initialized.

Once the model has performed 30 replications for a given response mode, subroutine EVNTS calls GASP IV subroutine COLCT to print summary statistics for that mode. Then the model determines whether all 5 modes have been simulated. If so, the model stops. But if not all of the response modes have been simulated, subroutine EVNTS reinitializes the number of replications performed to zero and calls subroutine INTLC. INTLC assigns the next mode and initializes the first activity of the first project under the next mode. The process is continued until 30 project replications have been simulated for all five management response modes. Thus, 150 project replications are simulated in each model run.

```
      IF(30 - NRN) 960,960,950
  950 CALL INTLC
      RETURN
  960 CALL COLCT(TNOW,0)
      IF(MODE.GE.5) STOP
      NRN = 0
      CALL INTLC
      RETURN
      END
```

Model Logic Flow Diagram

A graphical description of the model described in the previous section, is shown in Figure 3-1. Note how the EVNTS subroutine is used as the event subroutine, since there is only one type of event in the model.

Subroutine FILEM-(G)- File event attributes into file 1.

Return to GASP

A

At end of each project, EVNTS calls COLCT

Subroutine COLCT-(G)- Store values of total actual project duration and cost.

End of this mode? —— Yes —— B

No

B

At end of each mode, EVNTS calls COLCT

Subroutine COLCT-(G)- Compute and print statistics on total actual project duration and cost.

End of simulation run? —— Yes —— C

No

Initialize project for the next mode (NRN).

C

At end of the simulation run

Stop.

Figure 3-1. Model Logic Flow Diagram.

CHAPTER IV

RESULTS

The complete model described in the previous chapter was used for five simulation runs: a base run and four sensitivity runs. In this chapter the results of the base run will be described and analyzed in detail. Then they will be compared to the results obtained in each of the sensitivity runs.

A complete tabular display of results for all runs can be found in Appendix B.

At this point it seems important to reemphasize the following:

(1) Each project consisted of a one-path network of activities.

(2) For each of the five management response modes, 30 replications were performed for the base run and each sensitivity run.

(3) All activities in the network had the same quadratic time-cost tradeoff function.

(4) The relationship between indirect costs and project length was a linear function in all cases.

Base Run

For the base run of the model, several characteristics of the network were similar to those presented in the example of Chapter I (p.2).

(1) The quadratic time-cost tradeoff function used in this run of the model was the same as the one shown in equation (2) of Chapter I:

$$C = 15t_e^2 - 240t_e + 1,060$$

This was the direct cost curve for all activities in the network.

(2) The relationship between indirect costs and project length:

$$IC = 100 + 50(10)(t_e)$$

was similar to the one shown in equation (4) of Chapter I, the only difference being that the network in this model consisted of ten activities, whereas the example of Chapter I involved a five-activity network.

(3) The normal activity duration (TNORM) was eight days and the crash activity duration (TCRSH) was two days.

(4) The direct cost associated with the activity normal point (CNORM) was \$100.00 and the direct cost associated with

the activity crash point (CCRSH) was $640.00.

Also some other important assumptions of the model for this run were:

(5) The minimum value of the Beta distribution of activity durations (BMNFAC) was one half of the mean of that distribution. The maximum value (BMXFAC) was twice the mean of that distribution. These two values produced a variance for the Beta distribution (VAR) of 2.507 days for the calculated optimum activity duration.

With all the above assumptions, the planning stage of the model determined the following optimum values for the base run:

(1) Optimum activity duration (TOPT) = 6.333 days

(2) Optimum activity cost (COPT) = $ 141.67

(3) Optimum project duration (EPD) = 63.333 days

(4) Optimum total project cost (EPC) = $ 4683.33

Comparison of Results for the Base Run

One complete model simulation was performed for the base run and Table 4-1 shows the results obtained, comparing the various modes to the optimum values. The mean values in the table were computed from the 30 project replications under each mode. Several different performance criteria were compared, and the results of these comparisons are discussed next in the same order as shown in the table.

Table 4-1. Comparison of Results for the Base Run

Parameter	Optimum Value	Control Mode				
		1	2	3	4	5
1. Mean Project Duration (days)	63.33	63.47	61.37	61.71	68.86	66.41
2. Mean Total Project Cost ($)	4,683.00	4,693.00	4,744.00	4,728.00	4,824.00	4,757.00
3. Percentage Comparison of Means:						
a) Duration (%)	100.00	100.22	96.91	97.44	108.73	104.86
b) Cost (%)	100.00	100.21	101.30	100.96	103.01	101.58
4. Coefficients of Variation:						
a) Duration (dimensionless)	0.0000	0.0693	0.0425	0.0381	0.1410	0.1215
b) Cost (dimensionless)	0.0000	0.0678	0.0822	0.0800	0.0922	0.0839
5. Mean Direct Project Costs ($)	1,416.50	1,419.50	1,575.50	1,542.50	1,281.00	1,336.50
6. Multi-Criterion Coefficient (dimensionless)	1.000	1.004	0.982	0.984	1.120	1.065

(1) Mean project duration (days). This was a secondary criterion of interest in this study, and it was found that for the base run, the total project duration was minimized with mode 2. Moreover the ranking from best (shortest total project duration) to worst (longest total project duration) was as follows:

Mode 2 - Fast duration correction.

Mode 3 - Slow duration correction.

Mode 1 - Time-cost tradeoff.

Mode 5 - Slow cost correction.

Mode 4 - Fast cost correction.

This ranking is very logical, since modes 2 and 3 are only concerned with correcting duration deviations without regard to cost, while modes 5 and 4 are only concerned with correcting cost deviations without regard to duration. Note that the mean durations for modes 2 and 3 are lower than the optimum project duration. This is due to the fact that negative deviations (i.e., behind schedule) were corrected, but positive deviations were not corrected under these response modes.

(2) Mean total project costs ($). The primary performance criterion for this study was minimized as expected with mode 1. The order from best (least total project cost) to worst (greatest total project cost) was as follows:

Mode 1 - Time-cost tradeoff.

Mode 3 - Slow duration correction.

Mode 2 - Fast duration correction.

Mode 5 - Slow cost correction.

Mode 4 - Fast cost correction.

It is interesting to note that modes 3 and 2, which were concerned with correcting duration deviations without regard to cost, rank higher than modes 5 and 4, which were concerned with correcting cost deviations. This initially surprising result is due to the fact that response modes 4 and 5 attempted to correct the cost deviations by adjusting direct costs only. Hence by disregarding the effects of the indirect costs in the project, they actually increased the total project costs while attempting to reduce them.

(3) Percentage comparison of means:

Duration (%) and Cost (%). These percentages were obtained by dividing the means of the various modes by the optimum value for each criterion. The most interesting result of this comparison was the fact that none of the means obtained were very far away from the optimum values. Specially in the case of total project cost, the maximum deviation from the optimum value was only 3.01 percent.

(4) Coefficients of variation. These coefficients were

computed by dividing the standard deviations by the means for each criterion.

a) Duration (dimensionless). As might be expected, the variation in total project durations was minimized with mode 3. The reason is that the corrections in duration deviations were applied more gradually than in mode 2. The ranking of the modes from best (least variation) to worst (greatest variation) was as follows:

Mode 3 - Slow duration correction.

Mode 2 - Fast duration correction.

Mode 1 - Time-cost tradeoff.

Mode 5 - Slow cost correction.

Mode 4 - Fast cost correction.

This order shows that when the focus was on correcting the duration deviations, the variation in durations was also minimized. But when the focus was on correcting cost deviations, (without regard to durations), the variation in total project durations was increased significantly. In fact the coefficients of variation under modes 4 and 5 were about three times as large as the coefficient for mode 3.

b) Cost (dimensionless). An interesting result of this comparison between the modes was that the variation of total project costs was minimized with mode 1, the no change alternative.

Modes 4 and 5, which corrected cost deviations, did not fare well at all due to their lack of consideration of the indirect costs of the project. The ranking from best (least variation) to worst (greatest variation) was as follows:

Mode 1 - Time-cost tradeoff.

Mode 3 - Slow duration correction.

Mode 2 - Fast duration correction.

Mode 5 - Slow cost correction.

Mode 4 - Fast cost correction.

For the network under study, the comparison of coefficients of variation indicates that the first three modes will provide more stable results for project duration and total project costs, than those that can be obtained through the last two modes.

(5) Mean direct project costs ($). Another secondary criterion for this study, direct costs were minimized with mode 4 in the base run. This mode resulted in the lowest direct project costs, because it actually attempted to correct the deviation in total project costs as quickly as possible by adjusting direct costs only. For this criterion, therefore, mode 4 would be best. The obvious problem is that the indirect costs were not taken into consideration. In fact, as the direct costs were minimized in modes 4 and 5, the indirect costs were actually

maximized, thereby increasing the total project costs.

The order of the modes from best (least direct project costs) to worst (greatest direct project costs) was for this case:

Mode 4 - Fast cost correction.

Mode 5 - Slow cost correction.

Mode 1 - Time-cost tradeoff.

Mode 3 - Slow duration correction.

Mode 2 - Fast duration correction.

Moreover, Table 4-1 shows that the mean project direct costs for modes 4 and 5 were even less than the optimum value. This demonstrates that attempting to correct for total project costs by adjusting direct costs only is a highly undesirable, though perhaps not unusual, management response technique.

(6) Multi-criterion coefficient (dimensionless). A new criterion was developed in order to view each response mode in terms of its combined impact on total project cost and duration. This criterion will be called the multi-criterion coefficient (MCC). For each mode "i", it is computed as follows:

$$MCC_i = \frac{\text{Mean Cost}_i}{\text{Optimum Cost}} \times \frac{\text{Mean Duration}_i}{\text{Optimum Duration}}$$

The MCC is dimensionless. The relationship is such that increases in mean cost and mean duration both cause increases in the value of the MCC. The ranking of the management response modes from best (lowest MCC) to worst (highest MCC) was as follows:

Mode 2 - Fast duration correction.

Mode 3 - Slow duration correction.

Mode 1 - Time-cost tradeoff.

Mode 5 - Slow cost correction.

Mode 4 - Fast cost correction.

The MCC values for modes 2 and 3 are only slightly different. The fact that these modes yield the lowest values indicates that the increases in total project cost associated with these modes tend to be offset (percentagewise) by decreases in project duration for this particular case. The MCC also clearly shows the double detrimental impacts of modes 4 and 5.

Histograms

It was stated at the beginning of this chapter, that the mean values in Table 4-1 were computed from the 30 project replications under each mode. In this section the histograms of individual project durations and individual total project costs are presented and discussed briefly for each of the five control modes.

Figure 4-1 shows the histogram of individual project du-

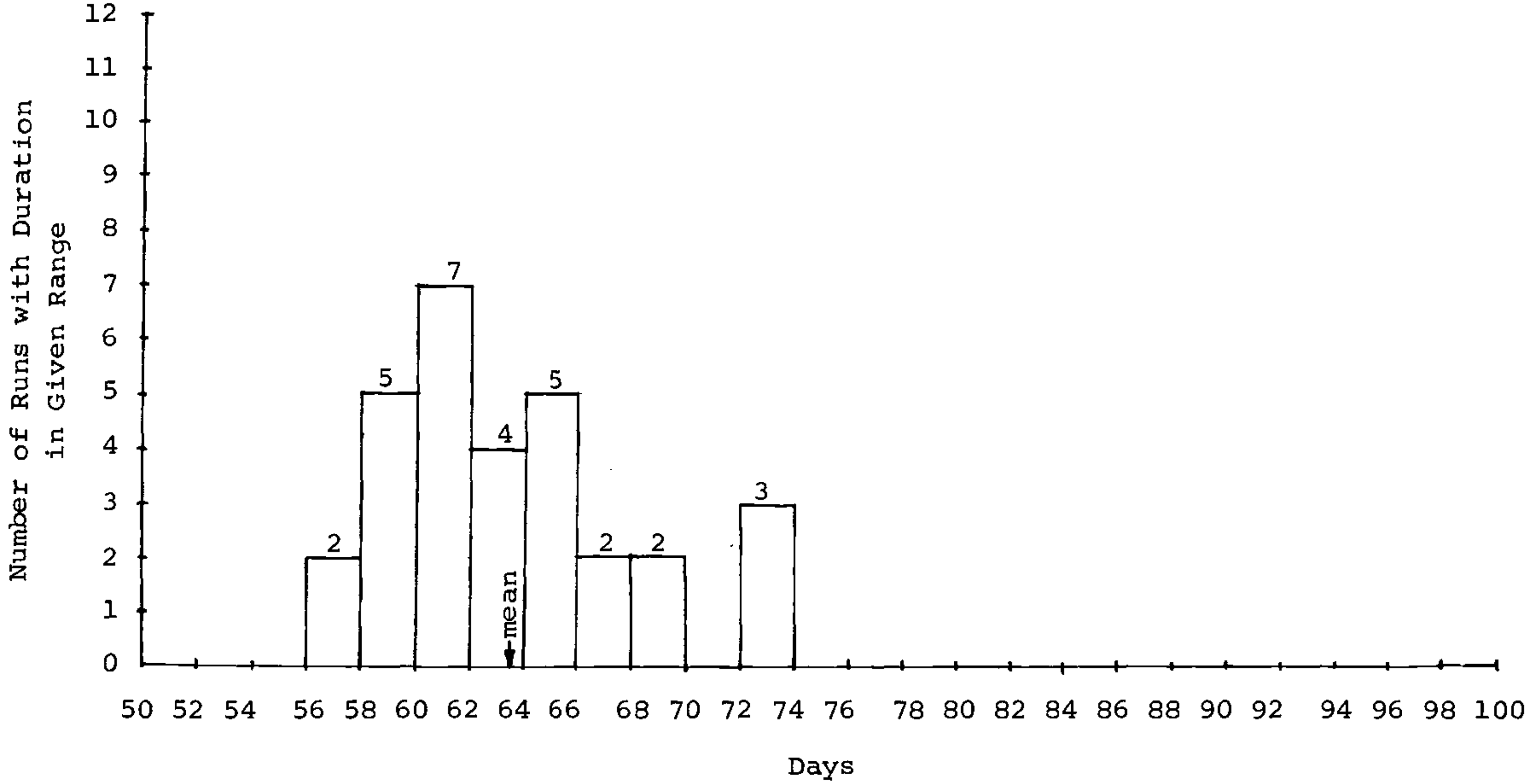


Figure 4-1. Histogram of Individual Project Durations Given Control Mode 1 of the Base Run.

rations under control mode 1 for the base run. Figures 4-2 and 4-3 are similar histograms for control modes 2 and 3. The means are shifted to the left slightly, and the variances are decreased for both cases. This improvement demonstrates again the ability of response modes 2 and 3 to control the project duration deviations in a consistent manner.

Figures 4-4 and 4-5 show similar histograms of individual project durations given control modes 4 and 5 of the base run. The inferior performance for these two modes when compared to the previous three modes is absolutely clear. Under modes 4 and 5, the means are shifted to the right, and the variances are greatly increased. Hence, these two response modes produce longer and more unstable project durations.

The histogram of individual total project costs for control mode 1 of the base run is shown in Figure 4-6. Figure 4-7 through 4-10 show similar histograms of individual total project costs for control modes 2 through 5. For all non-optimal modes, the mean is shifted slightly to the right, and the ranges are increased markedly. Thus it is shown that response mode 1 yields the lowest mean and most stable costs.

Variance Sensitivity Run

To test for the sensitivity of the results of the base run

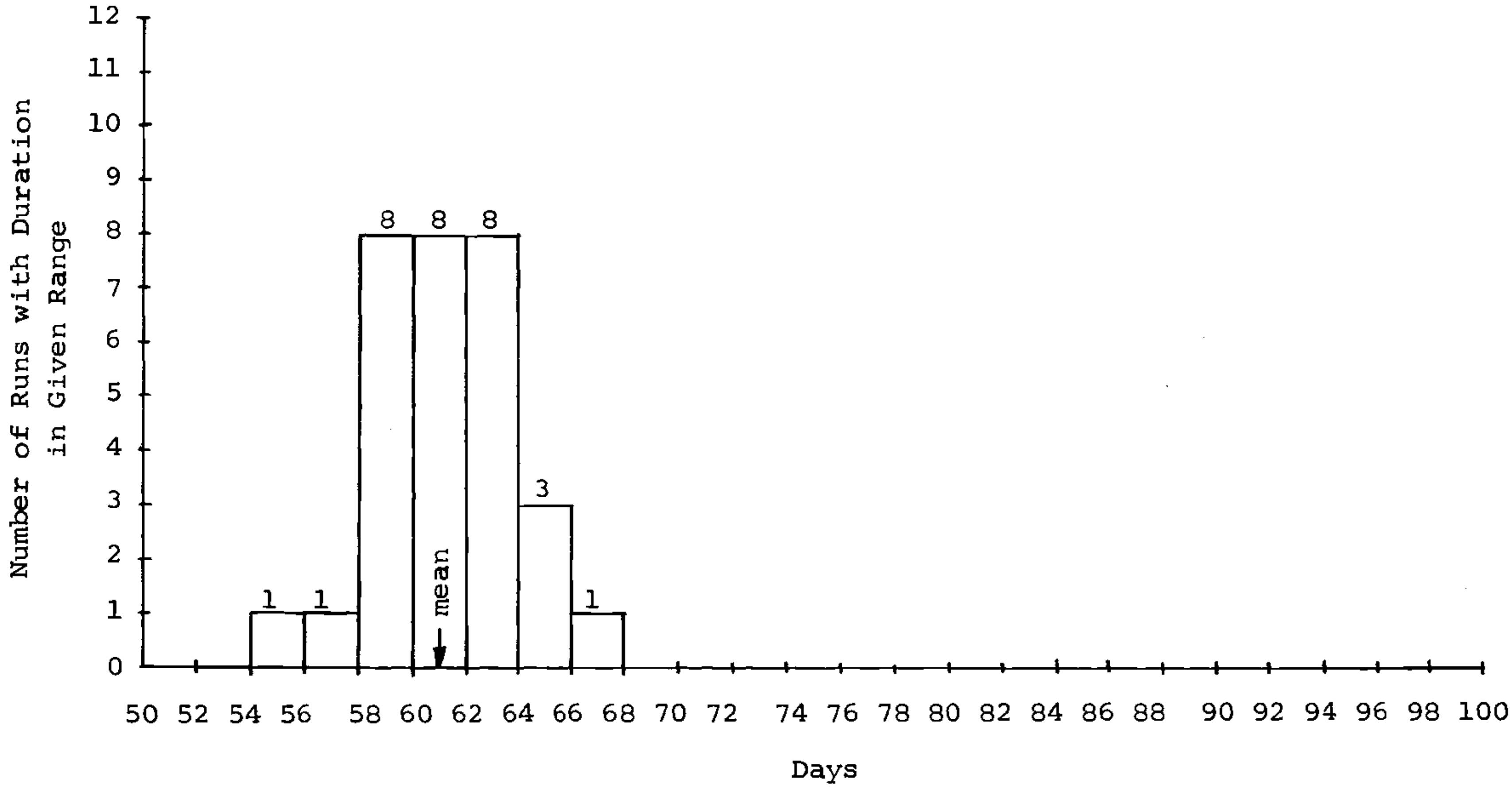


Figure 4-2. Histogram of Individual Project Durations
Given Control Mode 2 of the Base Run.

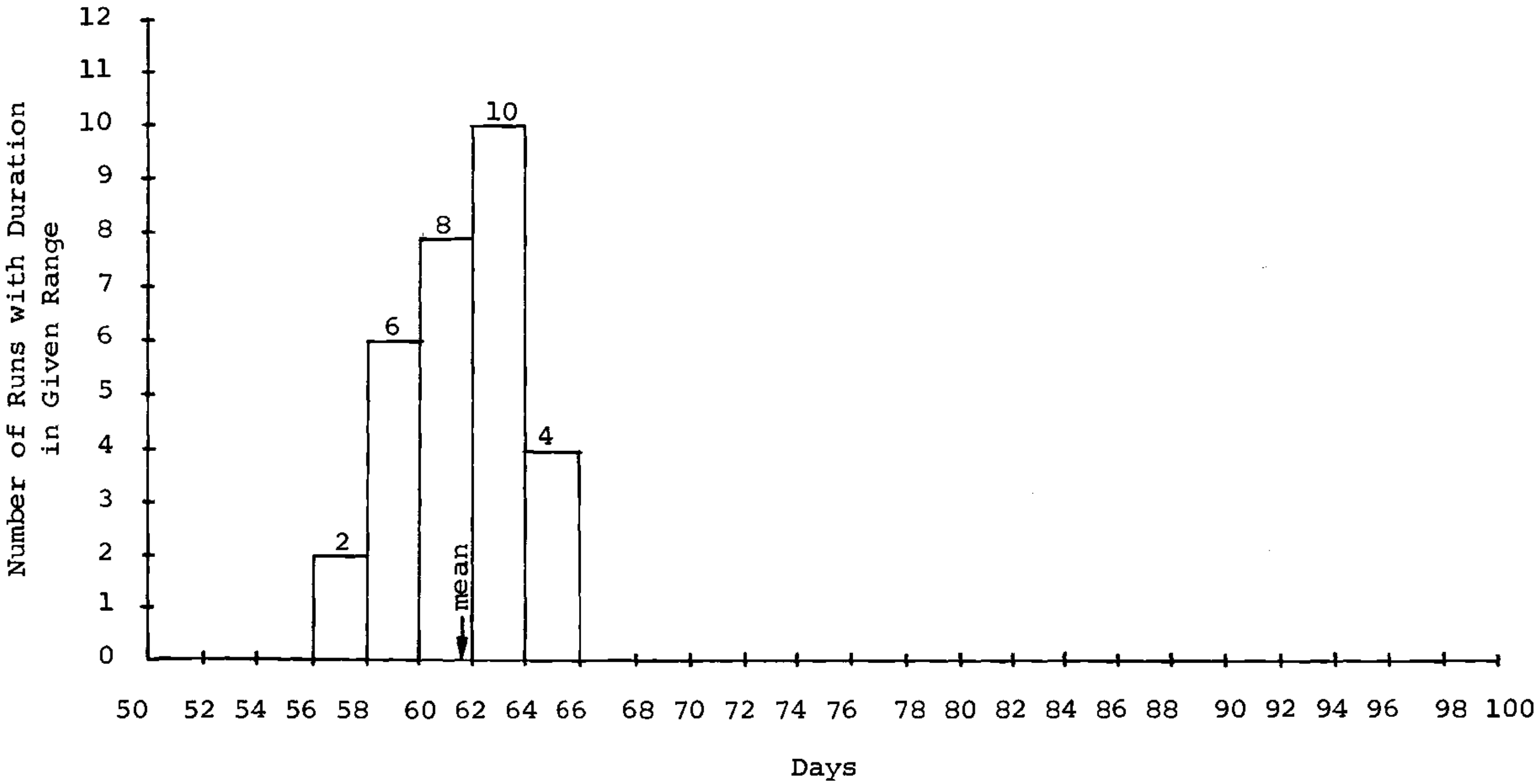


Figure 4-3. Histogram of Individual Project Durations Given Control Mode 3 of the Base Run.

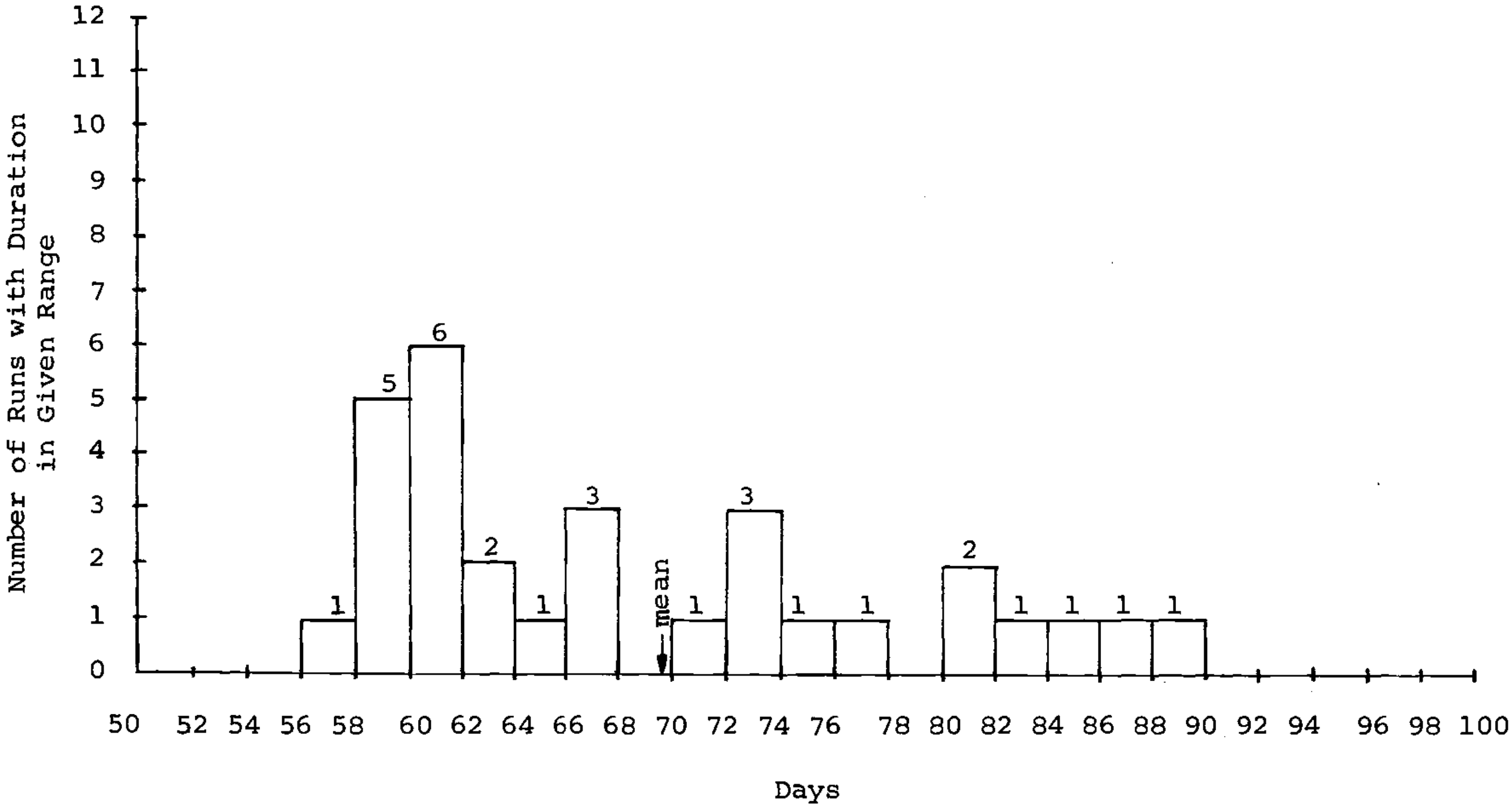


Figure 4-4. Histogram of Individual Project Durations
Given Control Mode 4 of the Base Run.

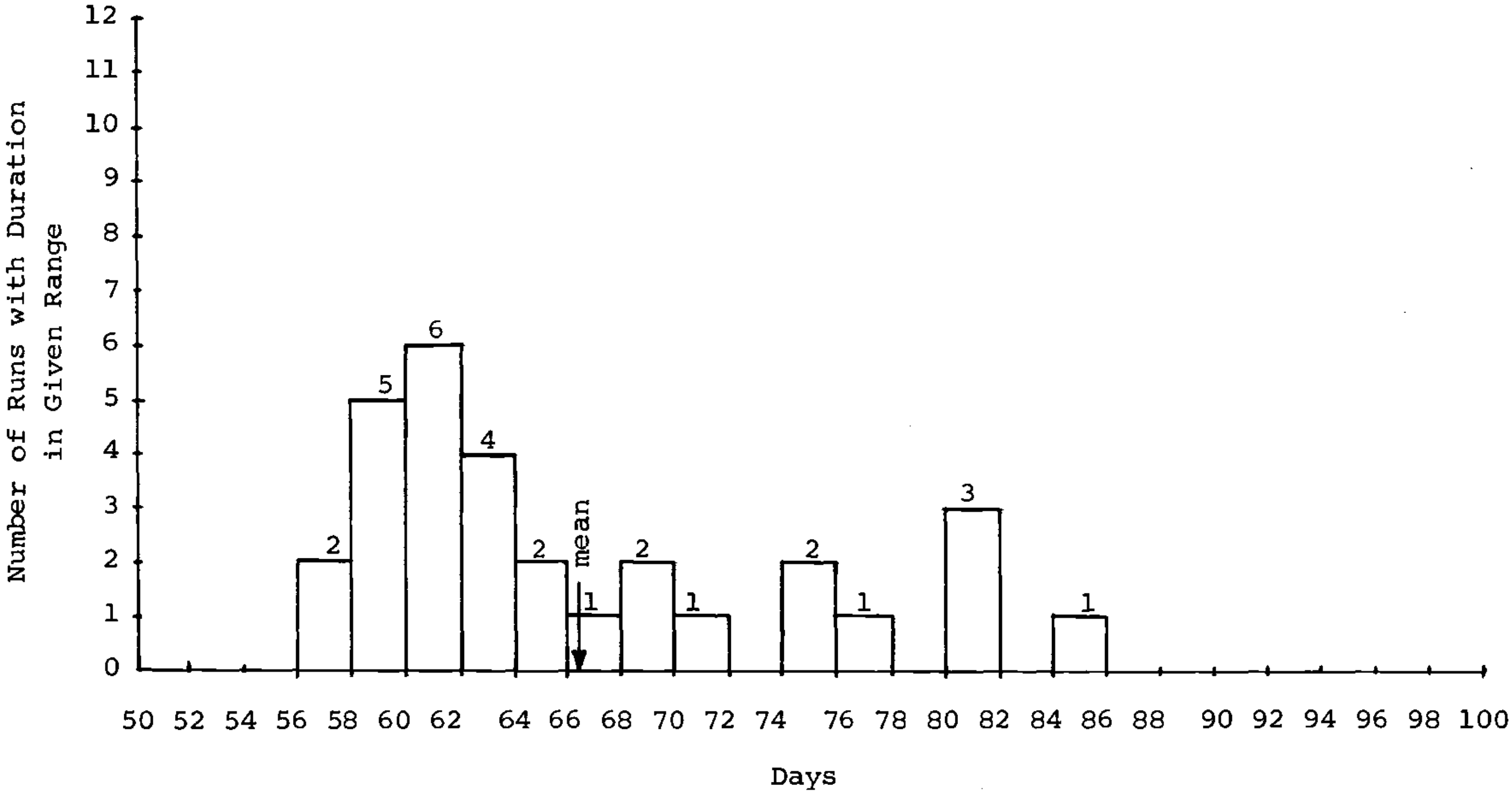


Figure 4-5. Histogram of Individual Project Durations Given Control Mode 5 of the Base Run.

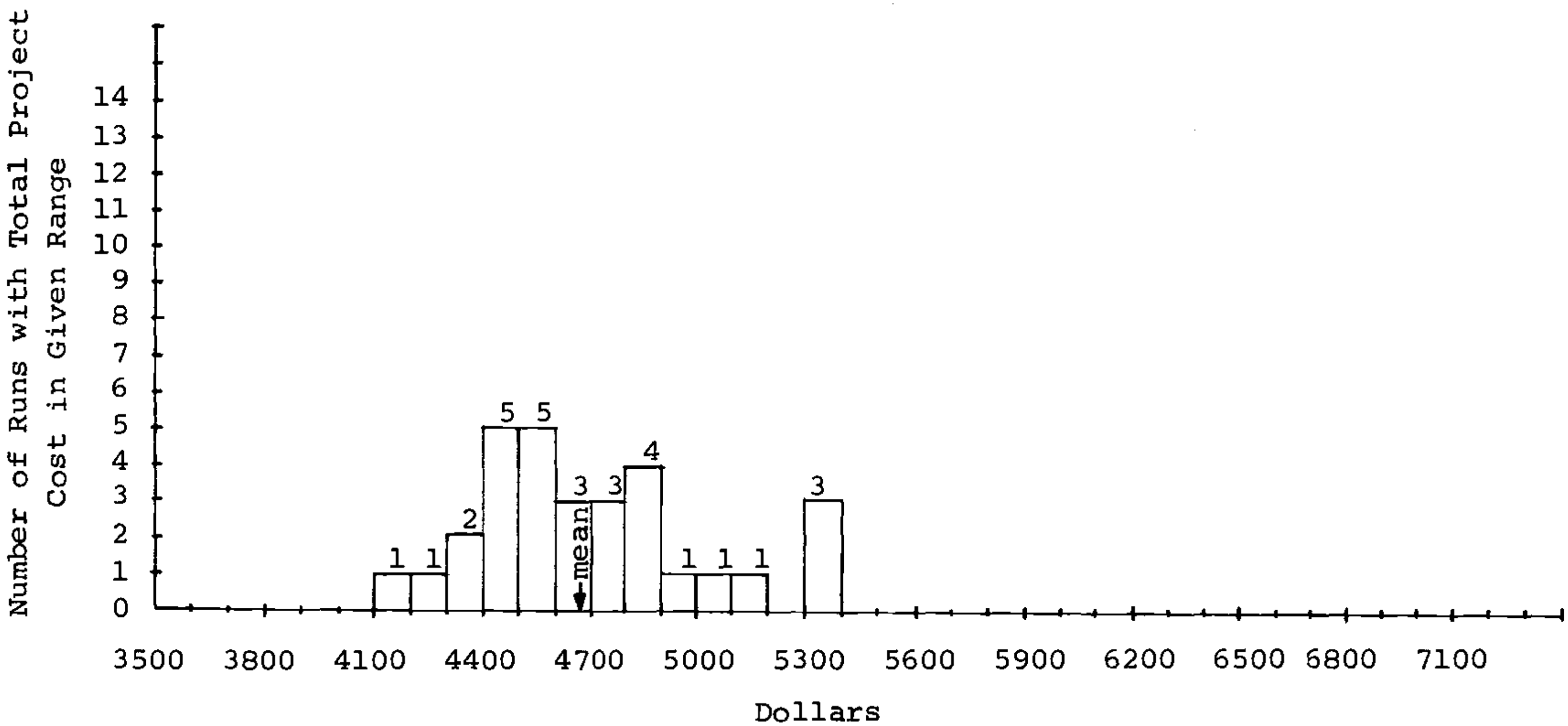


Figure 4-6. Histogram of Individual Total Project Costs
Given Control Mode 1 of the Base Run.

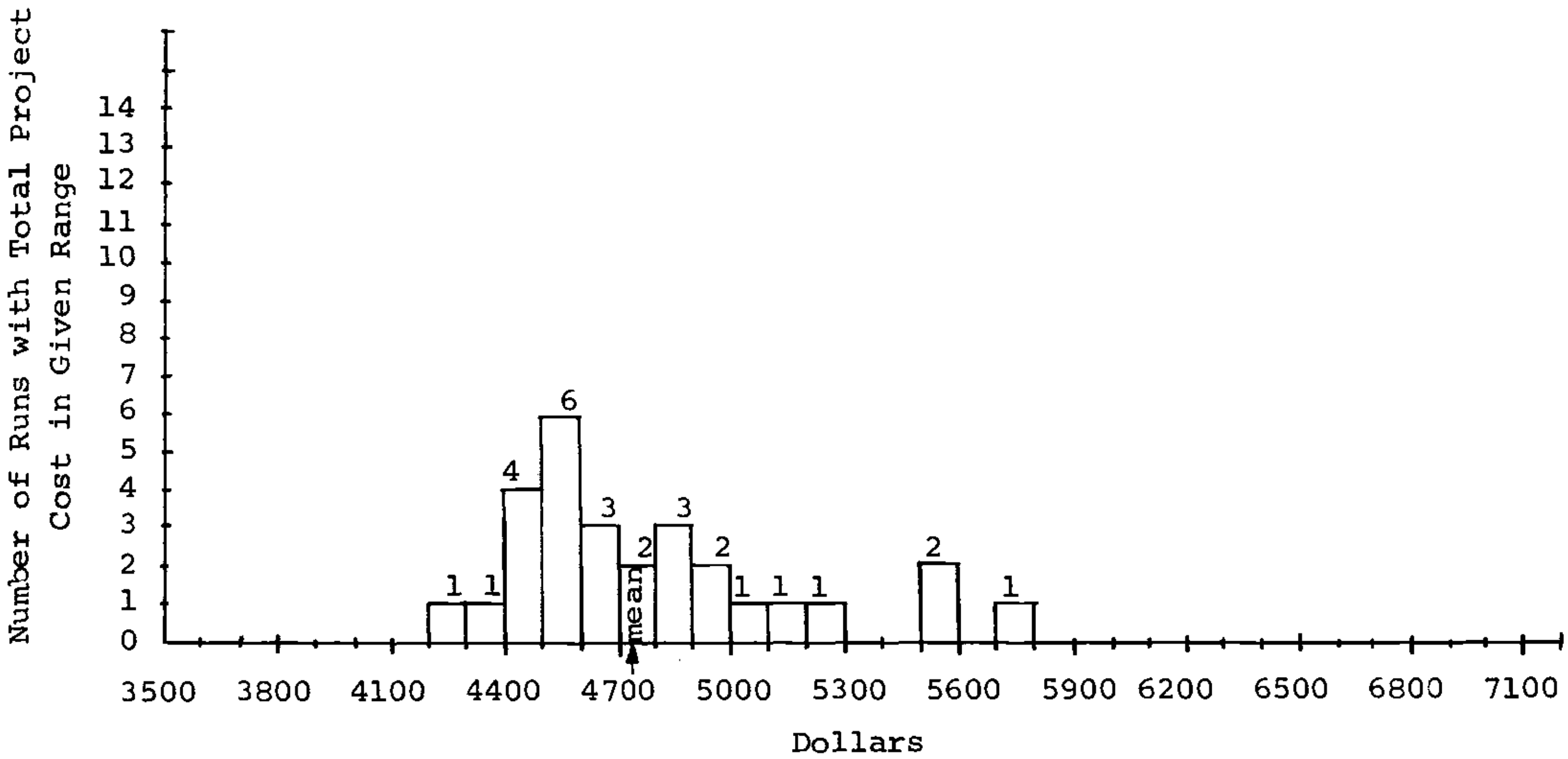


Figure 4-7. Histogram of Individual Total Project Costs
Given Control Mode 2 of the Base Run.

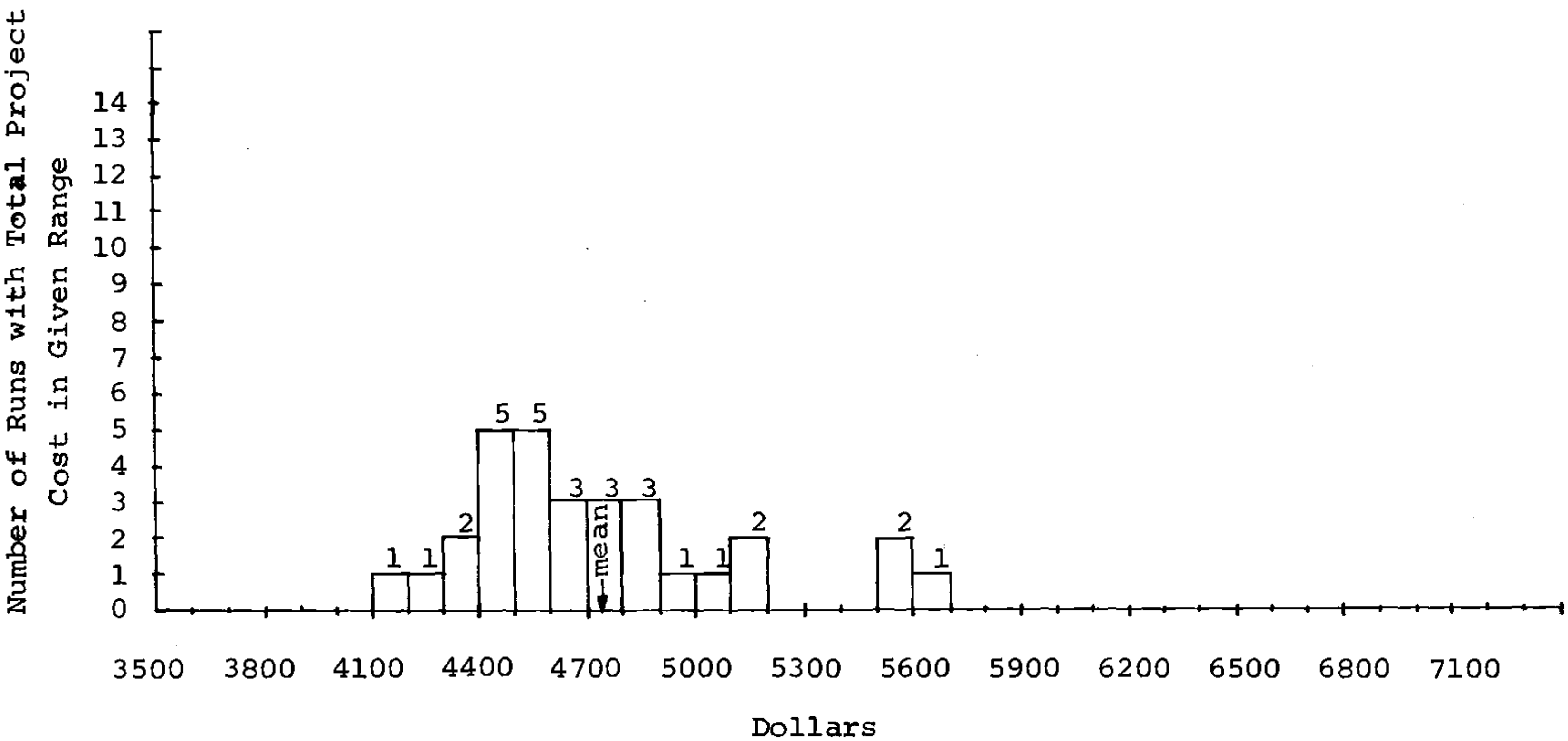


Figure 4-8. Histogram of Individual Total Project Costs Given Control Mode 3 of the Base Run.

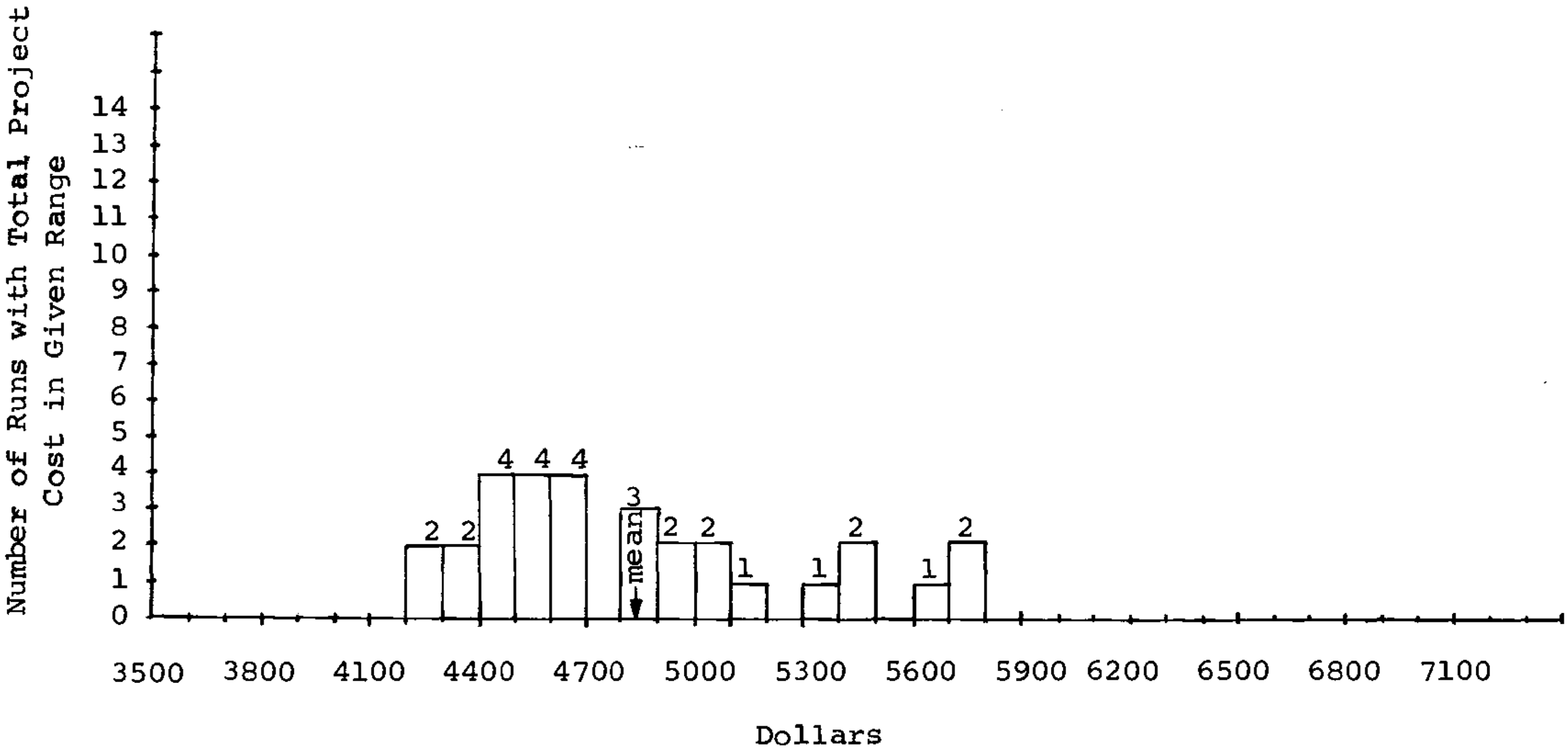


Figure 4-9. Histogram of Individual Total Project Costs
Given Control Mode 4 of the Base Run.

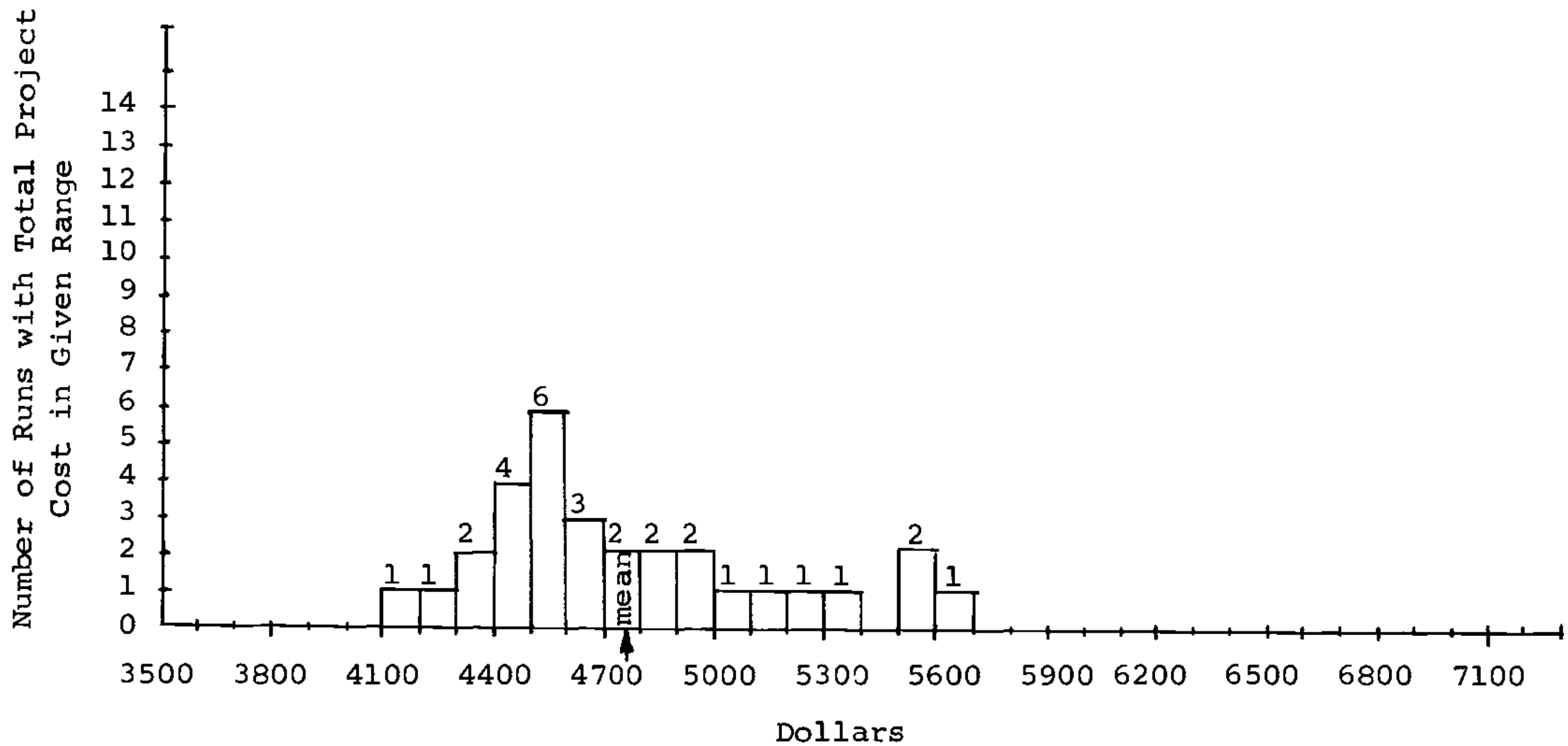


Figure 4-10. Histogram of Individual Total Project Costs Given Control Mode 5 of the Base Run.

to the variances of the activity duration distributions, the complete model was run again with a larger variance (VAR) for the Beta distribution. The minimum value of the Beta distribution of activity durations (BMNFAC) was set equal to 0.293 of the mean of that distribution (rather than 0.5, the value used in the base run). The maximum value (BMXFAC) was set equal to 2.414 of the mean of that distribution (rather than 2.000). These values produced a new variance for the Beta distribution (VAR) of 5.012 days, which was twice the variance in the base run.

Those were the only changes to the model for the variance sensitivity run; all other parameters remained exactly the same as in the base run.

With these assumptions, the planning stage of the model determined the following optimum values for the variance sensitivity run:

(1) Optimum activity duration = 6.333 days

(2) Optimum activity cost = $ 141.67

(3) Optimum project duration = 63.333 days

(4) Optimum total project cost = $ 4683.33

These optimum values were exactly the same as those obtained in the base run. As would be expected, the variance of the activity duration distribution has no effect in the planning stage; it only affects the stochastic simulation of the model itself.

Comparison of Results for the Variance Sensitivity Run

Table 4-2 shows the results obtained for one complete simulation of the model with the changes described above. All computations were performed in a similar manner to the base run, and the results of the comparisons of the various parameters considered are discussed next in the same order as shown in the table.

(1) Mean project duration (days). For this run the total project duration was minimized with response mode 2 as in the base run, and the order from best to worst project duration remained the same as in the base run. Therefore, these results were not affected by the change in variance.

(2) Mean total project costs ($). The total project cost was minimized under mode 1 as in the base run. However for the variance sensitivity run the order of the modes from best to worst changed as follows:

Mode 1 - Time-cost tradeoff.

Mode 3 - Slow duration correction.

Mode 5 - Slow cost correction.

Mode 2 - Fast duration correction.

Mode 4 - Fast cost correction.

Modes 5 and 2 have exchanged places in the ranking,

Table 4-2. Comparison of Results for the Variance Sensitivity Run

Parameter	Optimum Value	Control Mode 1	2	3	4	5
1. Mean Project Duration(days)	63.33	63.53	60.62	61.04	69.07	66.88
2. Mean Total Project Cost($)	4,683.00	4,697.00	4,788.00	4,763.00	4,833.00	4,771.00
3. Percentage Comparison of Means:						
a) Duration(%)	100.00	100.32	95.72	96.38	109.06	105.61
b) Cost(%)	100.00	100.30	102.24	101.71	103.20	101.88
4. Coefficients of Variation:						
a) Duration(dimensionless)	0.0000	0.0979	0.0597	0.0537	0.1687	0.1549
b) Cost(dimensionless)	0.0000	0.0958	0.1202	0.1184	0.1199	0.1136
5. Mean Direct Project Costs($)	1,416.50	1,420.50	1,657.00	1,611.00	1,279.50	1,327.00
6. Multi-Criterion Coefficient(dimensionless)	1.000	1.006	0.979	0.980	1.126	1.076

although there was only a slight difference in their mean costs in either of the two runs. The above re-ordering of the modes seems to emphasize the increased importance of gradual response modes when the variance of the activity duration distributions is large.

(3) Percentage comparison of means:

Duration (%) and Cost (%). In this run, as in the base run, none of the means obtained were very far from the optimum values, even though the variance of the activity duration distribution was twice as large.

(4) Coefficients of variation:

a) Duration (dimensionless). The ranking of the results obtained in the base run for this criterion remained unchanged for this sensitivity run, although the absolute magnitudes of the coefficients of variation were significantly increased for all modes by the increase in variance.

b) Cost (dimensionless). The variation of total project costs was minimized with mode 1, as it was in the base run, but the ranking from best to worst changed to:

Mode 1 - Time-cost tradeoff.

Mode 5 - Slow cost correction.

Mode 3 - Slow duration correction.

Mode 4 - Fast cost correction.

Mode 2 - Fast duration correction.

Again, as with the mean total project costs parameter, this re-ordering seems to point out that when the activity duration variance is very large, the gradual response modes are preferable with respect to cost control as compared to the faster modes.

(5) Mean direct project costs ($). Table 4-2 shows that for this run, as in the base run, mode 4 minimized direct costs. Moreover the ranking of the modes remained the same as in the base run. The absolute values of the direct costs, however, increased slightly for all modes.

(6) Multi-criterion coefficient (dimensionless). Neither the absolute values of the MCC nor the ranking of the modes were affected at all by the changes introduced in this run.

Histograms

Figure 4-11 shows the histogram of individual project durations under control mode 1 for the variance sensitivity run. By comparing this figure with Figure 4-1, which is the equivalent histogram for the base run, the effects of doubling the variance can be seen. The mean has not shifted, but the variance increased significantly. This behavior is to be expected due to the increase in variance in the activity duration distributions and the fact that mode 1 does not attempt to correct deviations.

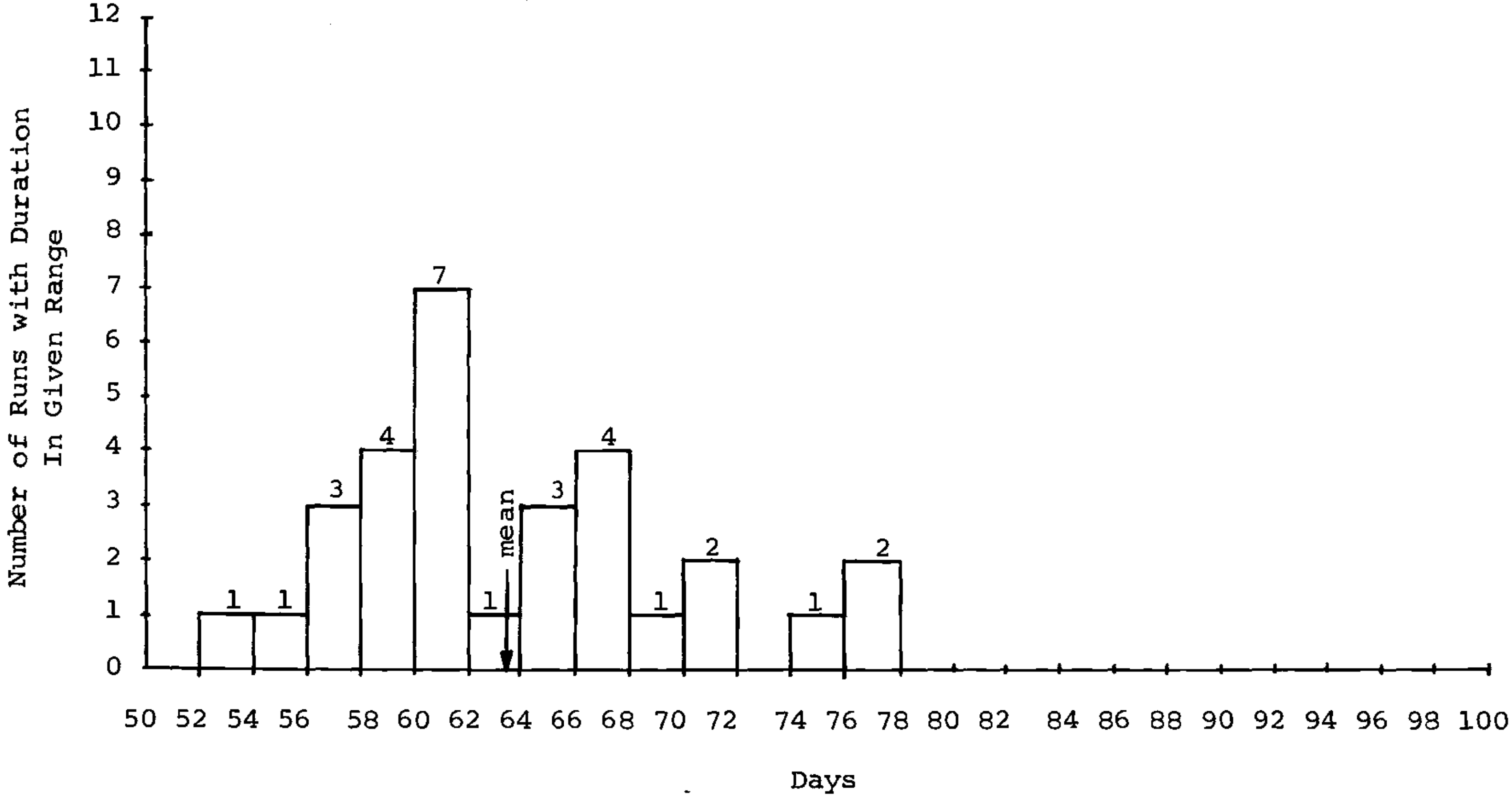


Figure 4-11. Histogram of Individual Project Durations Given Control Mode 1 of the Variance Sensitivity Run.

A histogram of individual total project costs under control mode 1 for the variance sensitivity run is shown in Figure 4-12. By comparing this figure with Figure 4-6, which is the equivalent histogram for the base run, it can be seen that the mean of the total project costs has not shifted, but the variance has increased.

Direct Cost Sensitivity Run

To test for the sensitivity to the direct cost slope, a new activity duration-direct cost tradeoff relationship was defined for this run. The new quadratic time-cost tradeoff function was:

$$DC = 30t_e^2 - 480t_e + 2020$$

Figure 4-13 shows the two direct cost curves so that the steepness of the two curves can be observed. Note that the "normal points" of the two curves coincide and that the second derivative of the new curve ($D_X^2DC_{dcs} = 60$) is twice that of the base run curve ($D_X^2DC_{br} = 30$). All other parameters were the same as for the base run.

With these assumptions, the planning stage of the model determined the following optimum values for the direct cost sensitivity run:

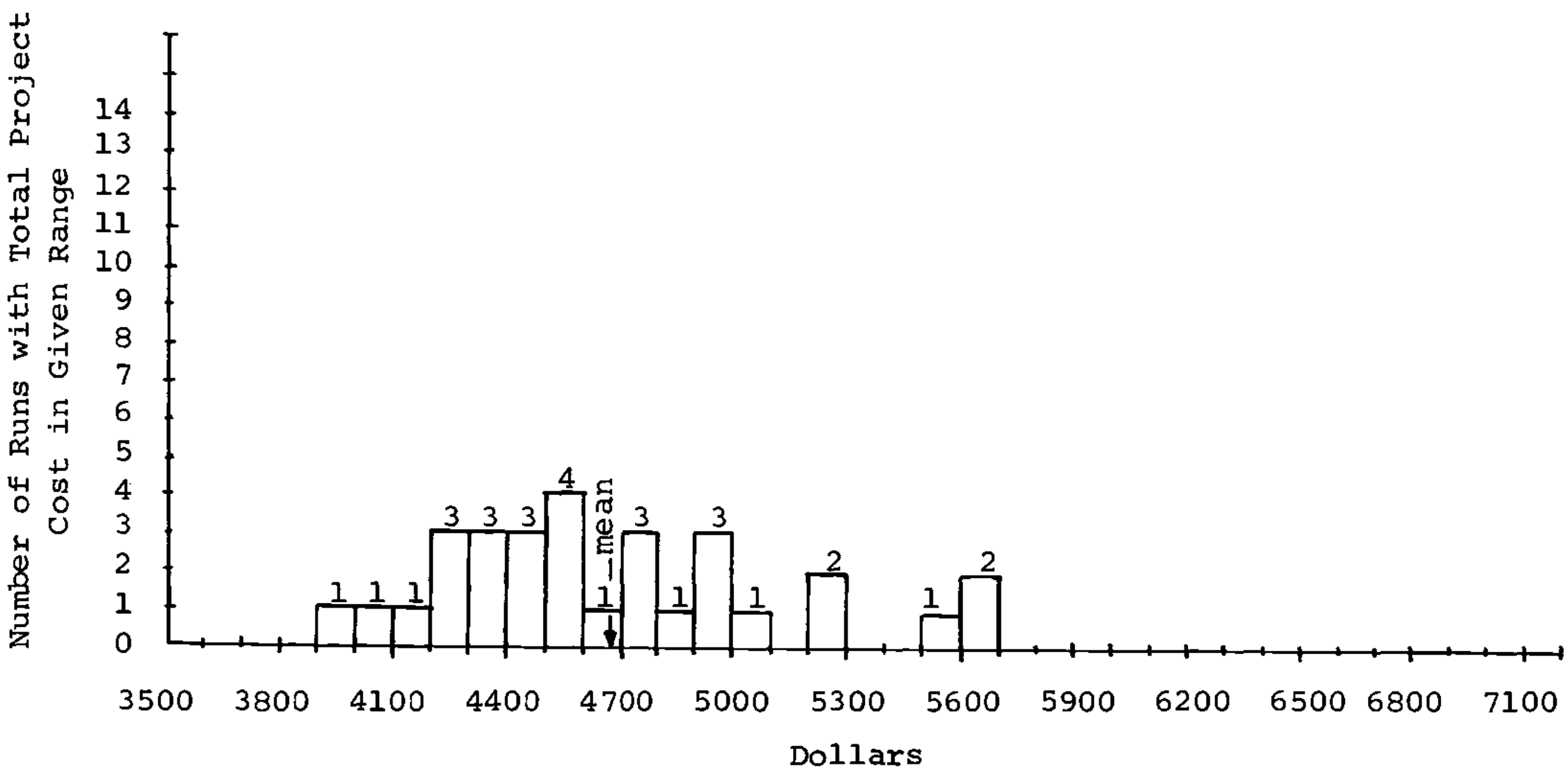


Figure 4-12. Histogram of Individual Total Project Costs Given Control Mode 1 of the Variance Sensitivity Run.

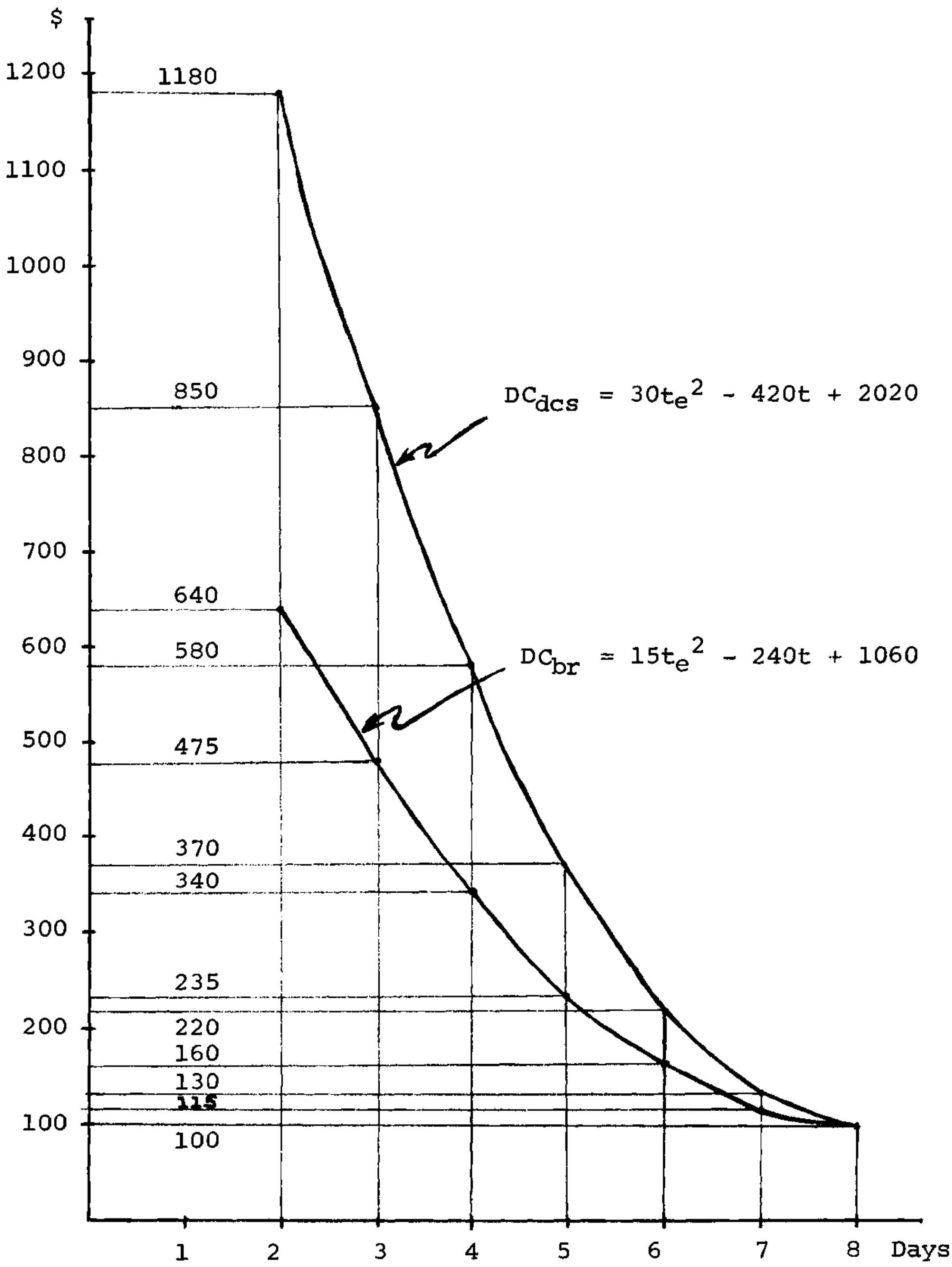


Figure 4-13. Direct Cost Curves.

(1) Optimum activity duration = 7.167 days

(2) Optimum activity cost = $ 120.83

(3) Optimum project duration = 71.667 days

(4) Optimum total project cost = $ 4,891.67

Due to the steeper direct cost curve, the optimum project plan involves a longer duration and higher total cost than for the base run.

Comparison of Results for the Direct Cost Sensitivity Run

The results for this run are shown in Table 4-3. The results of the comparisons for the various performance criteria are discussed below.

(1) Mean project duration (days). The ranking of the modes for this criterion remained the same as in the base run.

(2) Mean total project costs ($). The total project cost was minimized with mode 1 as in the base run. However the order of the modes from best to worst changed as follows:

Mode 1 - Time-cost tradeoff.

Mode 5 - Slow cost correction.

Mode 4 - Fast cost correction.

Mode 3 - Slow duration correction.

Mode 2 - Fast duration correction.

The results were sensitive to the new direct cost slope. Modes 4 and 5 became more effective due to the very steep direct

Table 4-3. Comparison of Results for the Direct Cost Sensitivity Run

Parameter	Optimum Value	Control Mode				
		1	2	3	4	5
1. Mean Project Duration (days)	71.67	71.82	69.44	69.83	74.68	73.76
2. Mean Total Project Cost ($)	4,892.00	4,902.00	5,033.00	4,990.00	4,972.00	4,946.00
3. Percentage Comparison of Means:						
a) Duration (%)	100.00	100.21	96.89	97.44	104.20	102.92
b) Cost (%)	100.00	100.20	102.88	102.00	101.64	101.10
4. Coefficients of Variation:						
a) Duration (dimensionless)	0.0000	0.0693	0.0425	0.0381	0.1007	0.0968
b) Cost (dimensionless)	0.0000	0.0679	0.1047	0.0986	0.0791	0.0775
5. Mean Direct Project Costs ($)	1,208.65	1,211.00	1,461.00	1,398.50	1,138.00	1,158.00
6. Multi-Criterion Coefficient (dimensionless)	1.000	1.004	0.997	0.994	1.059	1.041

cost function and the ability of these modes to control direct costs. The indirect costs of the project became less relevant.

(3) Percentage comparison of means:

Duration (%) and Cost (%). Again, as in the base run, none of the means obtained for this sensitivity run were very far from the optimum values.

(4) Coefficients of variation:

a) Duration (dimensionless). The ranking of the modes for this criterion remained unchanged from the base run. However, the magnitude of the coefficients decreased for modes 4 and 5.

b) Cost (dimensionless). The variation of total project costs was minimized with mode 1 as it was in the base run. The ranking of the response modes, however, changed to the following:

Mode 1 - Time-cost tradeoff.

Mode 5 - Slow cost correction.

Mode 4 - Fast cost correction.

Mode 3 - Slow duration correction.

Mode 2 - Fast duration correction.

This ranking shows again that the increased significance of the direct costs in the project improves the relative desirability of modes 4 and 5 with respect to cost control.

(5) Mean direct project costs ($). The ranking of the modes for this criterion remained the same as with the base run.

Modes 4 and 5 are still most effective, and mode 2 is least effective.

(6) Multi-criterion coefficient (dimensionless). Due to the steepness of the new direct cost curve, the order of the modes under this criterion was slightly changed from that of the base run, as follows:

Mode 3 - Slow duration correction.

Mode 2 - Fast duration correction.

Mode 1 - Time-cost tradeoff.

Mode 5 - Slow cost correction.

Mode 4 - Fast cost correction.

The only changes were in the first two modes, which exchanged places. This case points out that when the direct cost slope is very steep, it is better to correct for duration deviations with the slow response than with the fast response. The cumulative added cost of slight reductions in several activity durations is less than the added cost of a larger reduction in the next immediate activity. This effect is magnified by the greater steepness of the direct cost curve.

Histograms

Figure 4-14 shows the histogram of individual project durations under control mode 1 for the direct cost sensitivity run. Comparing this figure with Figure 4-1, the effects of the

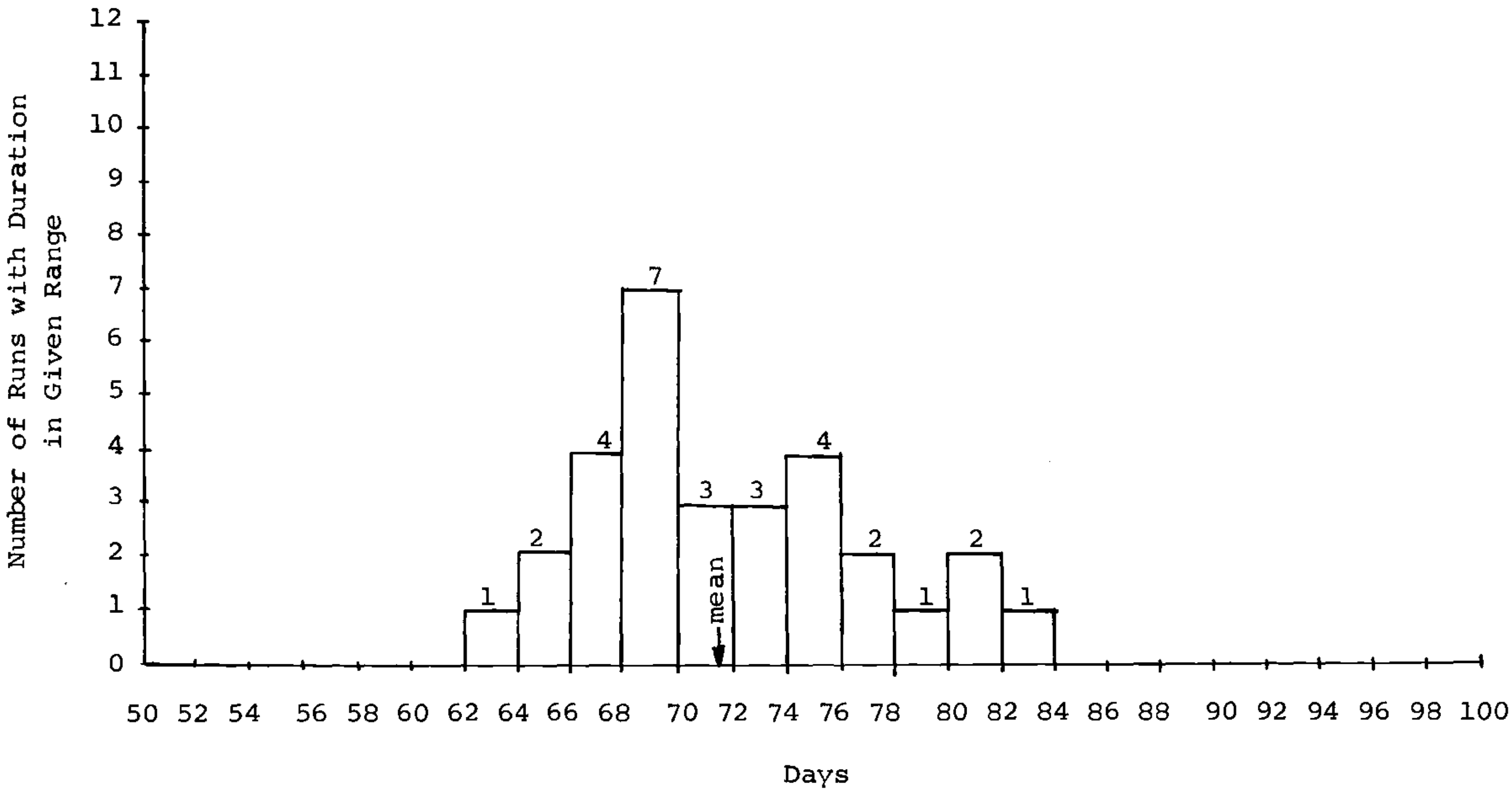


Figure 4-14. Histogram of Individual Project Durations Given Control Mode 1 of the Direct Cost Sensitivity Run.

increased steepness of the slope of the direct costs curve can be observed. The mean has shifted to the right, and the variance is slightly larger. The coefficient of variation for this mode, however, remained unchanged from the base run.

A histogram of individual total project costs under control mode 1 for the direct cost sensitivity run is shown in Figure 4-15. By comparing this histogram to Figure 4-6, it can be seen that the mean is shifted to the right, but the variance is not significantly changed.

Indirect Cost Sensitivity Run

To test for the sensitivity to the indirect cost slope, a new project duration-indirect cost relationship was defined. The new linear function was:

$$IC = 100 + 100(10)(t_e)$$

The slope of the function is twice as large as for the base run. All other parameters were the same as for the base run.

With these assumptions, the planning stage of the model determined the following optimum values for the indirect cost sensitivity run:

(1) Optimum activity duration = 4.667 days

(2) Optimum activity cost = $ 266.67

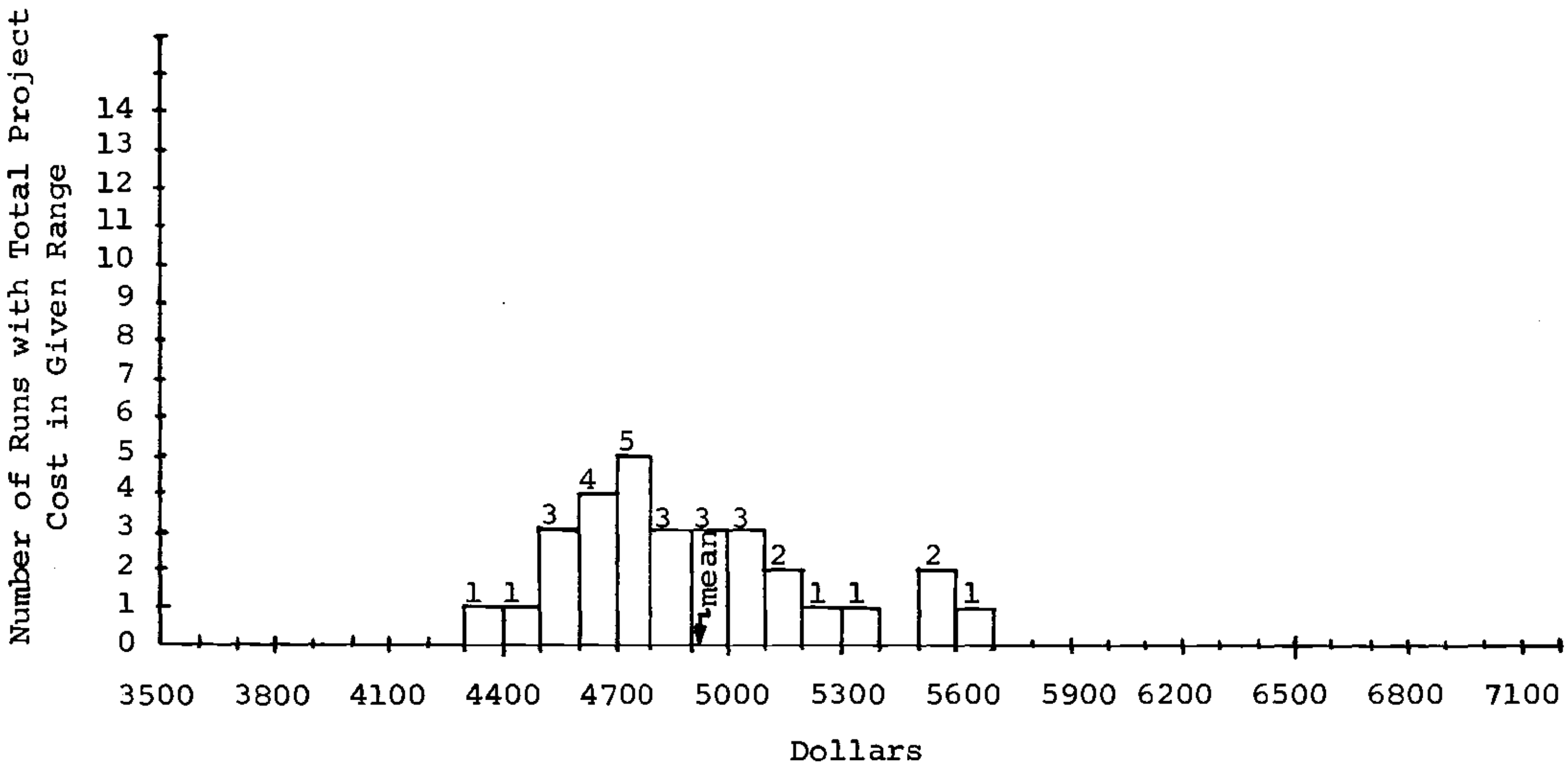


Figure 4-15. Histogram of Individual Total Project Costs Given Control Mode 1 of the Direct Cost Sensitivity Run.

(3) Optimum project duration = 46.667 days

(4) Optimum project cost = $ 7,433.33

Due to the steeper indirect cost function, the project should be performed more quickly, and the optimum total project cost is higher than for the base run.

Comparison of Results for the Indirect Cost Sensitivity Run

The results of the indirect cost sensitivity run are shown in Table 4-4.

(1) Mean project duration (days). The ranking of the modes for this criterion remained the same as in the base run.

(2) Mean total project costs ($). The ranking of the modes for the total project costs criterion remained the same as in the base run.

(3) Percentage comparison of means:

Duration (%) and Cost (%). Again, the means obtained for this sensitivity run were not very far from the optimum values, except for mode 4, where the mean duration was almost 20 percent larger than the optimum. The increased slope in the indirect cost curve caused modes 4 and 5 to be even less effective than they were in the base run, since they did not consider indirect costs.

(4) Coefficients of variation:

Duration (dimensionless) and Cost (dimensionless). For this

Table 4-4. Comparison of Results for the Indirect Cost Sensitivity Run

Parameter	Optimum Value	Control Mode				
		1	2	3	4	5
1. Mean Project Duration(days)	46.67	46.77	45.22	45.47	55.81	50.53
2. Mean Total Project Cost($)	7,433.00	7,449.00	7,476.00	7,468.00	7,862.00	7,594.00
3. Percentage Comparison of Means:						
a) Duration(%)	100.00	100.22	96.90	97.44	119.59	108.28
b) Cost(%)	100.00	100.22	100.58	100.47	105.77	102.17
4. Coefficients of Variation:						
a) Duration(dimensionless)	0.0000	0.0693	0.0425	0.0381	0.2450	0.1704
b) Cost(dimensionless)	0.0000	0.0683	0.0729	0.0724	0.1255	0.0960
5. Mean Direct Project Costs($)	2,666.00	2,672.00	2,854.00	2,821.00	2,181.00	2,441.00
6. Multi-Criterion Coefficient(dimensionless)	1.000	1.004	0.975	0.979	1.265	1.106

sensitivity run, the ranking of the modes for both of these criteria, remained the same as in the base run. The magnitudes of the coefficients increased, however, for modes 4 and 5.

(5) Mean direct project costs ($). Although the direct costs were increased substantially for all modes, the ranking of the modes for this criterion remained the same as with the base run.

(6) Multi-criterion coefficient (dimensionless). For this criterion also, the ranking of the modes remained unchanged from the base run. However, the magnitudes of the coefficients decreased (improved) for modes 2 and 3, and increased for modes 4 and 5.

Histograms

Figure 4-16 shows a histogram of individual project durations under control mode 1 for the indirect cost sensitivity run. Comparing this figure with Figure 4-1, the effects of the increased slope in the indirect cost relationship are seen. The mean is shifted to the left and the variance is decreased. This shows how a steep indirect cost function encourages the expediting of project progress.

By comparing Figure 4-17, which is the histogram of individual total project costs under control mode 1 for the indirect cost sensitivity run, with Figure 4-6, the effects of the

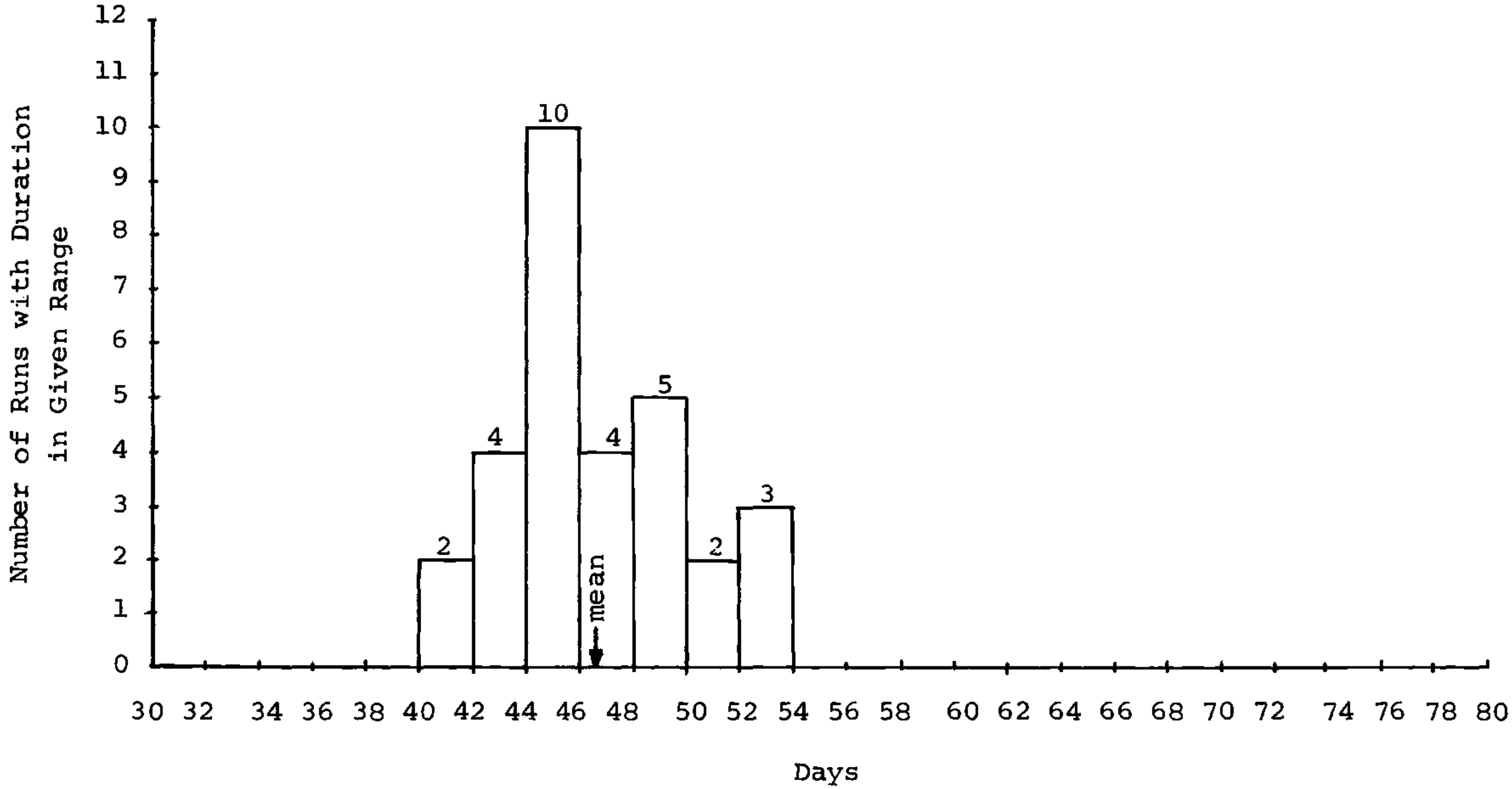


Figure 4-16. Histogram of Individual Project Durations Given Control Mode 1 of the Indirect Cost Sensitivity Run.

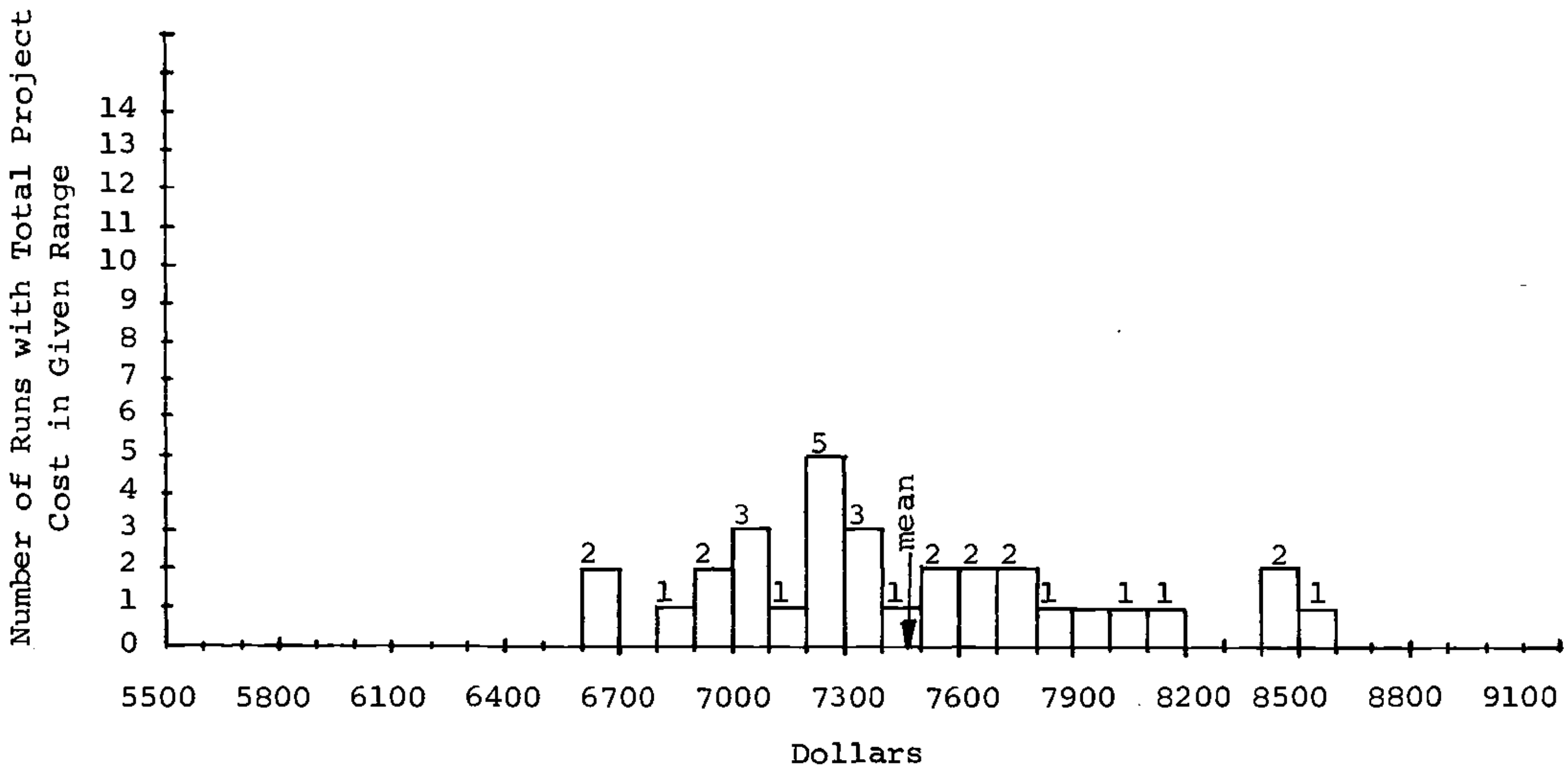


Figure 4-17. Histogram of Individual Total Project Costs Given Control Mode 1 of the Indirect Cost Sensitivity Run.

increased indirect cost function are seen. In Figure 4-17 the mean has shifted to the right and the variance is larger than in the base run. Therefore with the steeper indirect cost function, the project is performed more quickly, but at higher and less stable cost than in the base run.

Number-of-Activities Sensitivity Run

To test for the sensitivity to the number-of-activities in the network, the number was increased from ten to 20. All other parameters were the same as in the base run.

With these assumptions, the planning stage of the model determined the following optimum values for this sensitivity run:

(1) Optimum activity duration = 6.333 days

(2) Optimum activity cost = $ 141.67

(3) Optimum project duration = 126.667 days

(4) Optimum project cost = $ 9266.67

As would be expected the optimum project duration is double that of the base run.

Comparison of Results for the Number-of-Activities Sensitivity Run

The results of the sensitivity run are shown in Table 4-5.

(1) Mean project duration (days). The ranking of the modes for this criterion remained the same as in the base run.

Table 4-5. Comparison of Results for the Number-of-Activities Sensitivity Run

Parameter	Optimum Value	Control Mode 1	2	3	4	5
1. Mean Project Duration (days)	126.67	128.10	122.70	123.90	147.10	138.30
2. Mean Total Project Cost ($)	9,267.00	9,373.00	9,523.00	9,440.00	9,842.00	9,592.00
3. Percentage Comparison of Means:						
a) Duration (%)	100.00	101.13	96.87	97.82	116.13	109.18
b) Cost (%)	100.00	101.14	102.76	101.87	106.20	103.51
4. Coefficients of Variation:						
a) Duration (dimensionless)	0.0000	0.0601	0.0361	0.0347	0.1367	0.1140
b) Cost (dimensionless)	0.0000	0.0595	0.0713	0.0672	0.0863	0.0759
5. Mean Direct Project Costs ($)	2,833.65	2,868.00	3,288.00	3,145.00	2,387.00	2,577.00
6. Multi-Criterion Coefficient (dimensionless)	1.000	1.023	0.995	0.996	1.233	1.130

(2) Mean total project costs ($). The ranking of the modes for the total project costs criterion remained the same as in the base run.

(3) Percentage comparison of means:

Duration (%) and Cost (%). There was a slight increase in the percentage duration and cost deviations from the optimum values for all modes, as compared to the percentage deviations in the base run. The only two exceptions to that increase were the mean project durations for modes 2 and 3, which stayed about the same as in the base run. Still however, the mean values obtained for this sensitivity run were fairly close to the optimum values, with the exception of the mean project duration for mode 4, which was more than 16 percent larger than the optimum.

(4) Coefficients of variation:

Duration (dimensionless) and Cost (dimensionless). For this sensitivity run, the ranking of the modes for both of these criteria, remained the same as in the base run. However, the magnitudes of the coefficients decreased (improved) for all modes, indicating that increasing the number of activities in the network provides more stable results.

(5) Mean direct project costs ($). The ranking of the modes for this criterion remained the same as in the base run.

(6) Multi-criterion coefficient (dimensionless). Again

the ranking of the modes remained unchanged from the base run. However, the magnitudes of the coefficients increased (deteriorated) for all modes.

Histograms

Figure 4-18 shows the histogram of individual project durations, and Figure 4-19 shows the histogram of individual project costs under control mode 1 for the number-of-activities sensitivity run. Comparing these histograms with those shown in Figures 4-1 and 4-6 respectively for the base run, it can be seen that the means have approximately doubled and the ranges have decreased for both criteria.

Summary of Results

This section presents a brief summary of the results presented above. In the base run the various criteria examined showed the attractiveness of the first three modes and the inadequacy of modes 4 and 5 to correct either duration or cost deviations. It was found, as expected, that the total project costs were minimized with the time-cost tradeoff response (mode 1). This result held for all sensitivity runs. But in the base run it was also noted that modes 2 and 3 did save some time without incurring very large additional costs.

In the variance sensitivity run, the increased importance of gradual response modes was emphasized when the variance of

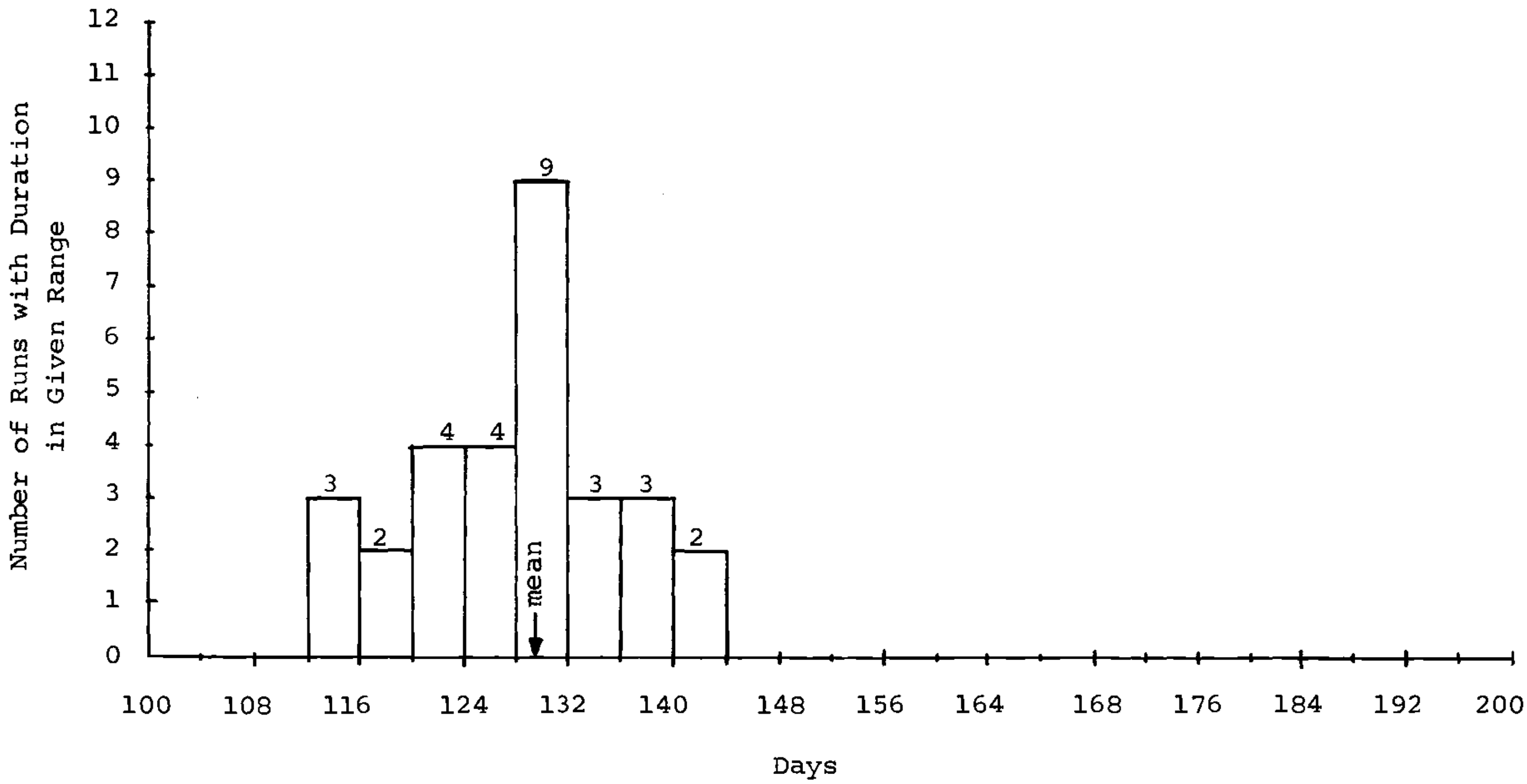


Figure 4-18. Histogram of Individual Project Durations Given Control Mode 1 of the Number-of-Activities Sensitivity Run.

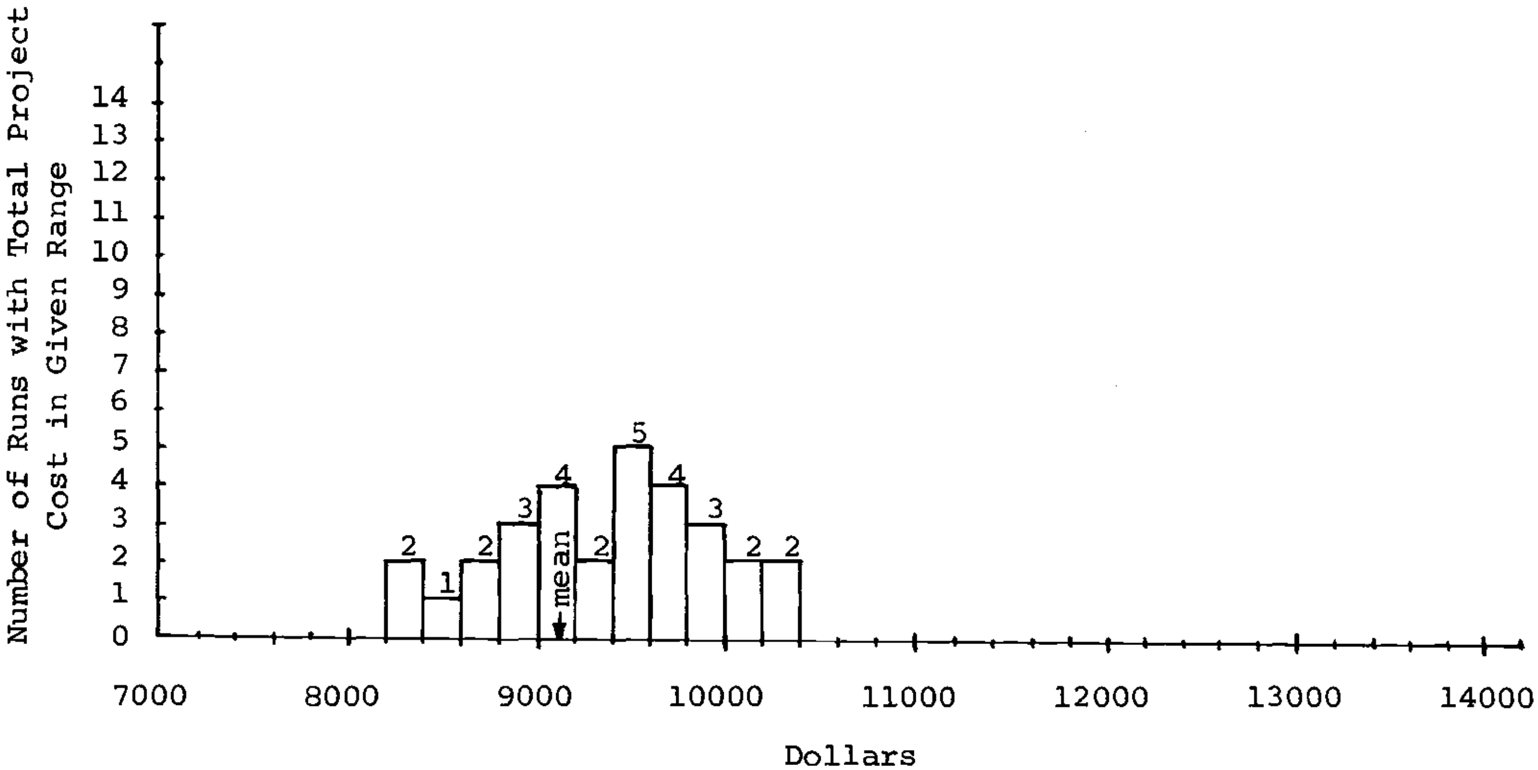


Figure 4-19. Histogram of Individual Total Project Costs Given Control Mode 1 of the Number-of-Activities Sensitivity Run.

the activity duration distributions is large.

The direct cost sensitivity run showed that when the direct cost function is very steep, modes 4 and 5 become much more effective, since the indirect costs of the project become less relevant.

The indirect cost sensitivity run simply reasserted the results obtained in the base run, demonstrating that they hold true for the case where the indirect costs are large.

In the number-of-activities sensitivity run, the relative performance of the various modes did not differ at all from the base run.

The multi-criterion coefficient presented in this chapter showed the combined impact of each response mode on total project cost and duration. For all runs modes 2 and 3 performed best on the basis of this criterion, indicating that the increases in total project cost associated with these modes tend to be offset (percentagewise) by decreases in project duration for all cases. The MCC also clearly showed the double detrimental impacts of modes 4 and 5 for all runs (including the direct cost sensitivity run).

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

Summary

This thesis has employed simulation to compare and evaluate several project control techniques with explicit recognition of time-cost tradeoffs and stochastic activity durations. The primary criterion for the evaluation of the techniques was total project cost, including both direct and indirect costs.

As expected, the optimum control mode with respect to the minimization of mean total project cost was one that involved performing a new time-cost tradeoff analysis for the remainder of the project at each project update. Such an approach, however, may be too laborious for many real-world project applications due to the quantity of data and computation required. Furthermore, most existing project control systems are driven by observed deviations from the project schedule and/or budget.

Therefore, the study analyzed the performance of four sub-optimal, though not necessarily atypical, management response modes for project control. Each of the four modes reacted to undesirable deviations either from the original optimum project schedule or from the budget associated with that schedule.

The four sub-optimal modes and the optimum mode were compared on the basis of several performance criteria in addition to mean total project cost. The results were tested for sensitivity to changes in major project parameters.

Conclusions

Several conclusions are drawn from the results of the study. As in any research, the conclusions should be viewed in the context of the limitations of the study, which have been stated earlier.

(1) For the range of project parameters considered, none of the sub-optimal management response modes produced catastrophic results on the average. In the worst cases:

a) The mean total project cost produced by one of the response modes (mode 4 in the number-of-activities sensitivity run) was 6.20 percent greater than the optimum cost.

b) The mean project duration produced by one of the response modes (mode 4 in the indirect cost sensitivity run) was 19.59 percent longer than the optimum duration.

(2) Control modes that react to negative duration deviations (i.e., project behind schedule) without explicit consideration of the impact of corrective actions on project costs

(modes 2 and 3) tend to increase direct costs, but effectively control indirect costs.

(3) Control modes that react to negative cost deviations (i.e., project over budget) by adjusting activity direct costs without explicit consideration of the impact on indirect costs (modes 4 and 5) tend to increase indirect costs while controlling direct costs.

(4) The overall impact of the sub-optimal response modes described in items 2 and 3 above on total project costs depends upon the relative slopes of the direct and indirect cost curves for the project. The greater the slope of the indirect cost curve relative to the direct cost curve, the more attractive are sub-optimal response modes that react to negative duration deviations (as compared to modes that react to negative cost deviations by adjusting direct costs only). In this study, indirect costs were an unusually large fraction of total costs. If the slope of the indirect cost curve were decreased to a more realistic value (relative to the direct cost curve) modes 4 and 5 would probably appear more generally desirable than they did in this study.

(5) If we consider total project duration as a separate performance criterion (in addition to the impact of project duration upon the indirect component of total project cost),

response modes that react to negative duration deviations (modes 2 and 3) tend to produce mean project durations that are shorter than the optimum value. The results with respect to the multi-criterion coefficient (MCC), which was defined in the study, show that for the range of project parameters considered, the percentage decrease in mean project duration caused by these sub-optimal modes is greater than the percentage increase in mean total cost. Although total project cost should be considered the primary performance criterion, the results indicate that the additional cost incurred with modes driven by negative duration deviations at least "buys" a reduction in duration.

(6) For most project parameters and performances criteria considered, response modes that attempted to correct duration or cost deviations gradually (modes 3 and 5) were found to be superior to modes that reacted more quickly (modes2 and 4). This conclusion assumes that there is no consistent bias in the actual activity durations relative to the planned mean of the activity duration distribution. Consistent errors may indicate problems in the planning process itself, rather than the randomness inherent in project activity durations.

Recommendations

The recommendations resulting from the study fall into two groups. First are recommendations directed to project managers:

(1) Project managers should explicitly recognize the dynamic nature of the time-cost tradeoff aspects of project control. At the start of a project, an optimum project schedule and budget may be developed with the objective of minimizing total project cost. As the project procedes, however, deviations from the initial optimum schedule and budget are likely to occur. The most appropriate response is to replan the remainder of the project as if it were a new project. This would include a new time-cost tradeoff analysis. Thus, it is more appropriate to develop a new optimum schedule and budget for the remainder of the project than to attempt to force the project back into correspondence with the original schedule and/or budget.

(2) When it is infeasible or impractical to perform new time-cost tradeoff analyses at each project update, managers may adopt one of several sub-optimal approaches to project control that involve correcting undesirable deviations from the original schedule or budget. When this is done, the project manager should be aware of the separate impacts of the response mode he selects on direct costs, indirect costs, and project

duration. The most desirable of several possible sub-optimal modes will be largely determined by the relative slopes of the direct and indirect cost slopes for the project.

(3) Project managers should avoid over-reacting to isolated undesirable deviations from schedule or budget that are caused by the stochastic nature of project activity durations and do not represent consistent trends. Correcting such deviations will involve some cost, and the undesirable stochastic deviations may be counter-balanced later in the project by desirable deviations.

The second set of recommendations relate to the extension of the research:

(1) The study should be replicated with more complex project networks, specifically networks involving several near-critical paths.

(2) It may be possible to identify and test other management response modes. An in-depth field study of common response modes is recommended.

(3) The current study could also be replicated with:

a) A much wider range of slopes for the indirect cost function.

b) Various nonlinear indirect cost functions.

c) Various forms of the activity direct cost function other than quadratic.

APPENDIX A

```
C       PRINT RESULTS OF PROJECT PLANNING PHASE

        WRITE(6,105) A,B,C1,C2,C3,VAR
    105 FORMAT(1H1,*A   = *,F5.0,5X,*B   = *,F5.0/
       1* C1 = *,F5.0,5X,*C2 = *,F5.0,5X,*C3 = *,F5.0/
       2* VARIANCE = *,F6.3,* DAYS*)
        WRITE(6,106) TNORM,TCRSH,CNORM,CCRSH
    106 FORMAT(1H0,*NORMAL TIME = *,F6.3,* DAYS*,5X,
       1*CRASH TIME = *,F6.3,* DAYS*/* NORMAL COST = $*,F7.2,8X,
       2*CRASH COST = $*,F7.2)
        WRITE(6,107) TOPT
    107 FORMAT(1H0,*OPTIMUM ACTIVITY DURATION = *F6.3* DAYS*)
        WRITE(6,108) COPT
    108 FORMAT(* OPTIMUM ACTIVITY COST = $*F6.2)
        WRITE(6,109) EPD
    109 FORMAT(1H0,*OPTIMUM PROJECT DURATION = *F7.3* DAYS*)
        WRITE(6,110) EPC
    110 FORMAT(* OPTIMUM PROJECT COST = $*F7.2)

        NRN=0
        CALL GASP
        END
```

```
C     SCHEDULE INITIAL EVENT

      ATRIB(1)=BETA(1,1)
      ATRIB(2)=ATRIB(1)*(COPT/TOPT)
      CALL FILEM(1)

      RETURN
      END
```

```
C     PRINT HEADINGS

      IF(NACT.GT.1) GO TO 5
      WRITE(6,101) NRN
  101 FORMAT(1H0/* RESULTS FOR RUN # *,I2)
      WRITE(6,102)
  102 FORMAT(1H0,10X,*DAYS AHEAD*,13X,*$ BELOW*/
     1* AFTER    (OR BEHIND)    %      (OR ABOVE)    %*/
     2*  ACT      SCHEDULE     DEV       BUDGET     DEV*/
     3* -----    -----------  -----    ----------  -----*)

    5 WRITE(6,901) NACT,TDEV,PTDEV,CDEV,PCDEV
  901 FORMAT(2X,I2,7X,F7.2,4X,F5.1,1H%,4X,1H$,F8.2,3X,F5.1,1H%)

C     GO TO APPROPRIATE CONTROL MODE

      IF(10-NACT) 700,700,10
   10 GO TO(100,200,300,400,500), MODE

C     CONTROL MODE # 1- TIME-COST TRADEOFF (NO CHANGE)

  100 BMU=TOPT
      GO TO 600

C     CONTOL MODE # 2 - FAST DURATION CORRECTION

  200 IF(TDEV) 201,100,100
  201 BMU=AMAX1(TOPT+TDEV, TCRSH)
      GO TO 600
```

```
C       DETERMINE EXPECTED COST AND ACTUAL DURATION OF NEXT ACTIVITY

        EXPCST=C1*(BMU**2.0)+C2*BMU+C3
        ADUR=BETA(1,1)

C       SCHEDULE NEXT EVENT

        ATRIB(1)=TNOW+ADUR
        ATRIB(2)=ADUR*(EXPCST/BMU)
        CALL FILEM(1)
        RETURN

  700   WRITE(6,902) TNOW,CCNOW
  902   FORMAT(1H0,*TOTAL PROJECT DURATION = *,F7.3,* DAYS*/
       1* TOTAL PROJECT COST = $*,F8.2)
        CALL COLCT(TNOW,1)
        CALL COLCT(CCNOW,2)

        IF(30-NRN) 960,960,950

  950   CALL INTLC
        RETURN

  960   CALL COLCT(TNOW,3)
        IF(MODE.GE.5) STOP
        NRN=0
        CALL INTLC
        RETURN
        END
```

Printout of Information Read by DATIN

```
NNCLT = 2    NNSTA = 0    NNHIS =  0   NNPRM = 1    NNPLT = 0    NNSTR = 1    NNTRY = 1
NNATR = 2    NNFIL = 1    NNSET = 20   NNEQD = 0    NNEQS = 0    NFLAG = 0
IIPOF = Y    IIPOS = Y    IISUM =  Y   IIPIR = Y

COLCT NO.   1             LLABC = DURATION
COLCT NO.   2             LLABC = COST

PRIORITY FILE             1 = FIFO

PARAMETER SET             1 =    .2333E+01     .3167E+01     .1267E+02     .7000E+01

MSTOP =     0  JJCLR = Y      JJBEG = Y      TTBEG = 0.     TTFIN = .1000E+21
JJFIL =     Y
IISED = 13579
```

Variable Definitions

A - The fixed component of the indirect cost function ($).*

ADUR - The actual duration of the next activity (days).

AMAXI - Fortran library function that identifies the larger of several values and assigns it to the respective variable.

ATRIB(I) - The attributes of the next simulation event, specifically the completion of the next activity, where:
ATRIB(1) = scheduled time of completion (days).
ATRIB(2) = actual direct cost of the activity ($).**

B - The slope of the indirect cost function ($/day).*

BETA(1,1) - GASP IV function which generates a Beta deviate using parameter set 1 and random number stream 1 (days).

BMN - The minimum value of the Beta distribution of activity durations (days).

BMNFAC - The minimum value of the Beta distribution of activity durations expressed as a fraction of the mean of that distribution (dimensionless).*

BMU - The mean of the Beta distribution of activity durations from which the next activity duration will be generated (days).

BMX - The maximum value of the Beta distribution of activity durations (days).

BMXFAC - The maximum value of the Beta distribution of activity durations expressed as a multiple of the mean of that distribution (dimensionless).*

C1,C2,C3 - Coefficients of the quadratic activity duration-direct cost tradeoff function ($/day^2, $/day, $).*

CCRSH - Direct cost associated with the activity crash (i.e., minimum duration) point ($).

CDEV - The deviation between actual and budgeted cumulative total project cost at the current state of completion ($), where:
CDEV – 0 indicates budget – actual.
CDEV – 0 indicates budget – actual.

CNEXT - Target direct cost for the next activity ($).

CNORM - Direct cost associated with the activity normal (i.e., minimum direct cost) point ($).

CNOW - Cumulative actual direct costs ($).

CCNOW - Cumulative actual total cost ($).

COPT - Direct cost associated with the optimum activity duration ($).

DBA - Difference between the maximum and minimum values of the Beta distribution of activity durations (days).

DBM - Difference between the maximum and mean values of the Beta distribution of activity durations (days).

DMA - Difference between the mean and minimum values of the Beta distribution of activity durations (days).

DRAND(ISTRM) - GASP IV function that generates pseurandom numbers on the interval (0,1) from stream ISTRM. A call to DRAND with a negative argument causes the generator to be reinitialized.

ECOST - Expected total project cost at the current state of completion, assuming optimum activity durations ($).

EPC - Expected total project cost at completion, assuming optimum activity durations ($).

EPD - Expected total project duration assuming optimum activity durations (days).

ETIME - Expected time at which the current state of completion should have been reached, assuming optimum activity durations (i.e., originally scheduled completion time for the activity just completed) (days).

EXPCST - Expected direct cost for the next activity based upon the mean of the Beta distribution of activity durations ($).

MODE - Switch for determining management response mode, where:
MODE = 1 indicates optimum mode.
MODE = 2 indicates fast duration correction.
MODE = 3 indicates slow duration correction.
MODE = 4 indicates fast cost correction.
MODE = 5 indicates slow cost correction.
(dimensionless).

NACT - Number of the activity just completed (dimensionless).

NCRDR - Device number assigned to the card reader for use by GASP subroutines (dimensionless).**

NRN - Number of the current run (project) replication (dimensionless).

NSET(20) - File vector used by GASP system (dimensionless).**

PCDEV - CDEV as a percentage of ECOST (%).

PPARM(1,I) - Parameters required by function Beta to generate stochastic activity durations from the appropriate Beta distribution.**

PTDEV - TDEV as a percentage of ETIME (%).

QSET(20) - Equivalent to NSET.**

REMACT - Number of activities remaining to be processed in the project (dimensionless).

SQRT - Fortran library function that computes the square root of its argument.

TCRSH	-	The crash (i.e., minimum possible) activity duration (days).*
TDEV	-	The deviation between the scheduled and actual time at which the current state of completion was reached (days), where: TDEV _ 0 indicates ahead of schedule. TDEV _ 0 indicates behind schedule.
TNORM	-	The normal (i.e., minimum direct cost) activity duration (days).*
TNOW	-	Current time (days).**
TOPT	-	The optimum activity duration (days).
VAR	-	Variance of the Beta distribution of activity durations ($days^2$).
X	-	Dummy variable used only in resetting the random number generator (dimensionless).

* Model inputs.
** GASP IV variables.

APPENDIX B

Table B-1. Comparison of Project Duration and Total Project Cost Means (days and $)

Case	Optimum Value	Control Mode				
		1	2	3	4	5
1. Base Run						
Project Duration(days)	63.33	63.47	61.37	61.71	68.86	66.41
Total Project Cost($)	4,683.00	4,693.00	4,744.00	4,728.00	4,824.00	4,757.00
2. Direct Cost Sensitivity Run						
Project Duration(days)	71.67	71.82	69.44	69.83	74.68	73.76
Total Project Cost($)	4,892.00	4,902.00	5,033.00	4,990.00	4,972.00	4,946.00
3. Indirect Cost Sensitivity Run						
Project Duration(days)	46.67	46.77	45.22	45.47	55.81	50.53
Total Project Cost($)	7,433.00	7,449.00	7,476.00	7,468.00	7,862.00	7,594.00
4. Variance Sensitivity Run						
Project Duration(days)	63.33	63.53	60.62	61.04	69.07	66.88
Total Project Cost($)	4,683.00	4,697.00	4,788.00	4,763.00	4,833.00	4,771.00
5. Number-of-Activities Sensitivity Run						
Project Duration(days)	126.67	128.10	122.70	123.90	147.10	138.30
Total Project Cost($)	9,267.00	9,373.00	9,523.00	9,440.00	9,842.00	9,592.00

Table B-2. Percentage Comparison of Means (%)

Case	Optimum Value	Control Mode				
		1	2	3	4	5
1. Base Run						
Project Duration(days)	100.00	100.22	96.91	97.44	108.73	104.86
Total Project Cost($)	100.00	100.21	101.30	100.96	103.01	101.58
2. Direct Cost Sensitivity Run						
Project Duration(days)	100.00	100.21	96.89	97.44	104.20	102.92
Total Project Cost($)	100.00	100.20	102.88	102.00	101.64	101.10
3. Indirect Cost Sensitivity Run						
Project Duration(days)	100.00	100.22	96.90	97.44	119.59	108.28
Total Project Cost($)	100.00	100.22	100.58	100.47	105.77	102.17
4. Variance Sensitivity Run						
Project Duration(days)	100.00	100.32	95.72	96.38	109.06	105.61
Total Project Cost($)	100.00	100.30	102.24	101.71	103.20	101.88
5. Number-of-Activities Sensitivity Run						
Project Duration(days)	100.00	101.13	96.87	97.82	116.13	109.18
Total Project Cost($)	100.00	101.14	102.76	101.87	106.20	103.51

Table B-3. Comparison of Coefficients of Variation (dimensionless)

Case	Optimum Value	Control Mode				
		1	2	3	4	5
1. Base Run						
Project Duration (days)	0	0.0693	0.0425	0.0381	0.1410	0.1215
Total Project Cost ($)	0	0.0678	0.0822	0.0800	0.0922	0.0839
2. Direct Cost Sensitivity Run						
Project Duration (days)	0	0.0693	0.0425	0.0381	0.1007	0.0968
Total Project Cost ($)	0	0.0679	0.1047	0.0986	0.0791	0.0775
3. Indirect Cost Sensitivity Run						
Project Duration (days)	0	0.0693	0.0425	0.0381	0.2450	0.1704
Total Project Cost ($)	0	0.0683	0.0729	0.0724	0.1255	0.0960
4. Variance Sensitivity Run						
Project Duration (days)	0	0.0979	0.0597	0.0537	0.1687	0.1549
Total Project Cost ($)	0	0.0958	0.1202	0.1184	0.1199	0.1136
5. Number-of-Activities Sensitivity Run						
Project Duration (days)	0	0.0601	0.0361	0.0347	0.1367	0.1140
Total Project Cost ($)	0	0.0595	0.0713	0.0672	0.0863	0.0759

Table B-4. Comparison of Mean Direct Project Costs ($)

Case	Optimum Value	Control Mode				
		1	2	3	4	5
1. Base Run Direct Project Cost	1,416.50	1,419.50	1,575.50	1,542.00	1,281.00	1,336.50
2. Direct Cost Sensitivity Run Direct Project Cost	1,208.65	1,211.00	1,461.00	1,398.50	1,138.00	1,158.00
3. Indirect Cost Sensitivity Run Direct Project Cost	2,666.00	2,672.00	2,854.00	2,821.00	2,181.00	2,441.00
4. Variance Sensi- tivity Run Direct Project Cost	1,416.50	1,420.50	1,657.00	1,611.00	1,279.50	1,327.00
5. Number-of-Activities Sensitivity Run Direct Project Cost	2,833.65	2,868.00	3,288.00	3,145.00	2,387.00	2,577.00

Table B-5. Comparison of Multi-Criterion Coefficients (MCC) (dimensionless)

Case	Optimum Value	Control Mode				
		1	2	3	4	5
1. Base Run MCC		1.004	0.982	0.984	1.120	1.065
2. Direct Cost Sensitivity Run MCC		1.004	0.997	0.994	1.059	1.041
3. Indirect Cost Sensitivity Run MCC		1.004	0.975	0.979	1.265	1.106
4. Variance Sensitivity Run MCC		1.006	0.979	0.980	1.126	1.076
5. Number-of-Activities Sensitivity Run MCC		1.023	0.995	0.996	1.233	1.130

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